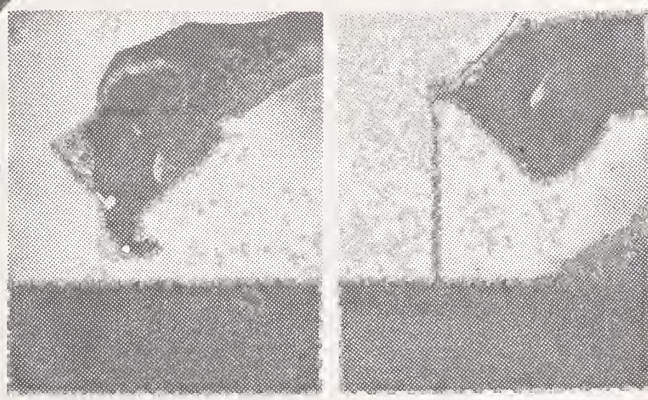
Report No. FHWA/RD-80/132

VALUATION OF SUPER-WATER REDUCERS FOR IGHWAY APPLICATIONS

March 1981
Final Report



FLOW OF CEMENT PASTE WITHOUT SUPER WATER REDUCER
WATER-CEMENT RATIO=0.25

FLOW OF CEMENT PASTE WITH 1% SUPER WATER REDUCER
WATER-CEMENT RATIO=0.25

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Prepared for
FEDERAL HIGHWAY ADMINISTRATION
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FOREWORD

This report summarizes an investigation of the use of a new variety of admixtures in portland cement concrete. The new admixtures, typically referred to as "super water reducers" or "high range water reducers," permit the production of workable concrete at much lower water-cement ratios than can be achieved using conventional water reducing admixtures. As a result, many of the engineering properties of the portland cement concrete are improved. It will be of interest to materials, construction and maintenance engineers.

The study involved the characterization and evaluation of both naphthalene and melamine sulfonated formaldehyde condensate admixtures in various low-water cement ratio, high strength concretes for highway construction applications. The most promising area of application of these products appears to be in the production of dense, high-cement content concrete "on-site" using mobile concrete mixers. Such mixers are now frequently available and often used for thin-bonded bridge deck overlays. A users guide, covering both on-site mobile and ready-mix use of the admixtures, is included in the report.

Sufficient copies of the report are being distributed to provide a minimum of one copy to each FHWA regional office, one copy to each FHWA division office, and two copies to each State highway agency. Direct distribution is being made to the division offices.

Charles F. Scheffey
Charles F. Scheffey
Director, Office of Research

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16. Abstract

"Super-Water Reducers" were characterized and evaluated as potential candidates for production of low water-to-cement ratio, high strength concretes for highway construction applications. Admixtures were composed of either naphthalene or melamine sulfonated formaldehyde condensates. A mini-slump procedure was used to assess dosage requirements and behavior of workability with time of cement pastes. Required dosage was found to be a function of tricalcium aluminate content, alkali content, and fineness of the cement.

Concretes exhibited high rates of slump loss when super-water reducers were used. Slump loss was found to be a function of cement and admixture composition, dosage of admixture, time of addition of admixture, concrete paste contents, and temperature. Based on results of this testing, the use of these admixtures in central mix paving operations is not recommended.

Incorporation of super-water reducers into conventional concretes was found to alter the entrained air system. Use of higher initial plastic air contents of 7-8 percent is recommended. The most promising area of application of these products appears to be in production of dense, high cement content concrete using mobile concrete mixer/transporters.

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1. Introduction

During the past few years a new class of admixtures has appeared on the U.S. market. Variously termed "super" water-reducers (SWR), high-range (ASTM Designation: C494-80) water-reducers, or "super" plasticizers, they represent a class of compounds which have the ability to reduce net water contents of concrete mixtures up to 30 percent. These admixture have the potential for producing very high strength durable portland cement concrete while still utilizing conventional mixing and placement techniques. In the highway field, there are a number of very attractive uses for these admixtures, among which can be listed:

1. Production of premium grade, "zero-maintenance" PCC pavements.

2. Improvement in the quality (i.e., increased strength and reduced permeability) of concrete used in reinforced concrete bridge decks.

3. Production of very low water-cement (w/c) ratio PCC overlays without resort to heavy vibration usually needed for these materials.

4. Production of precast elements using lower temperature and/or shorter steam cycles.

5. Plasticization of conventional concrete mixtures, allowing placement in congested, heavily reinforced members and reducing placement times and manual labor involved.

This research program emphasized the first three items. That is, pavement, bridge deck, and overlay applications. The research was materials oriented, use of the materials in actual construction being outside the scope of the project. The objective of the program was to determine, from the properties of the concretes prepared with the super water-reducers, whether further development work was warranted, and what applications held the most promise.

The actual use of these materials in highway field applications has not proceeded at as great a rate as one might expect for admixtures having such potential. Although cost is certainly a factor, early experiences with these admixtures highlighted two major areas of concern. These are an increased rate of loss of workability ("slump loss"), and a degradation in the durability of concretes prepared with super water-reducers under freeze-thaw conditions. Although these two areas were under investigation by many researchers at the time the present program was initiated, no practical solutions had been found. Indeed, there was, and still is, much controversy as to the causes of these problems. One of the major aims of this research was to gather more information in these two areas, so as to allow an eventual identification of the causes of and possible solutions to these problems.

2. Chemical and Physical Properties of SWR

2.1 SWR Used in This Study

The SWR used in this study were commercially available at the time the program was initiated (Spring 1977). Seven products were chosen for the initial phase of the program. Summary information on these products is given in Table 1.

2.2 Chemical Analyses of SWR

The SWR used in this study belong to two major chemical classes. The first of these are the sulfonated condensation products of naphthalene-formaldehyde (Figure 1A). Included in this class are Mighty 150, Lomar D, Sikament, and WRDA-19. The second class, sulfonated melamine formaldehyde condensation products (Figure 1B), is represented by Melment L-10. The product FX-32C was found to be a blend of both types of raw materials. Alkanol appeared to be chemically similar to the naphthalene-formaldehyde products. It must be emphasized that these chemical structures are only meant to be typical of the two general classes of admixtures. They are not the actual structure of each admixture. Although further work was done utilizing spectrophotometric techniques (Appendix 1), complete chemical structural analyses of each admixture was beyond the scope of the program.

The admixtures were analyzed for those substances known to be important in terms of their action in portland cement concrete. Tests for pH, soluble chlorides, sulfates, alkalies (sodium and potassium), and total sulfur, were run on the seven SWR. Results are presented in Table 2. None of the admixtures contain sufficient amounts of deleterious ions (Cl^-, $SO_4^=$, Na^+) to be considered harmful. The contribution of the admixture towards total alkali content in a rich concrete mixture, however, may become significant at higher dosages (2 percent

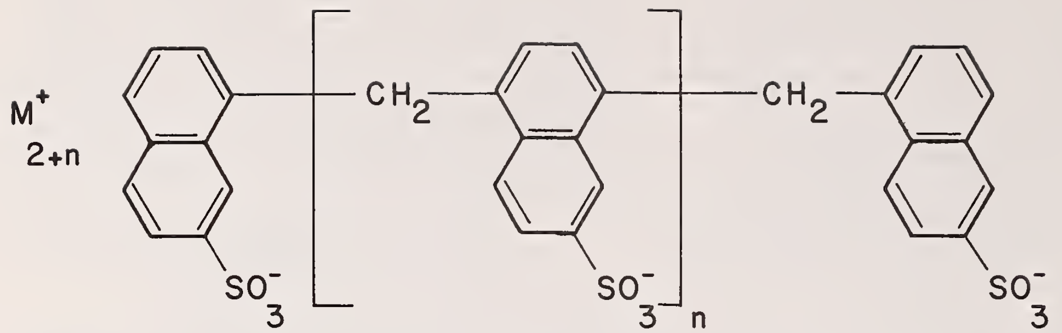

FIGURE 1A. SULFONATED NAPHTHALENE-FORMALDEHYDE CONDENSATION PRODUCT

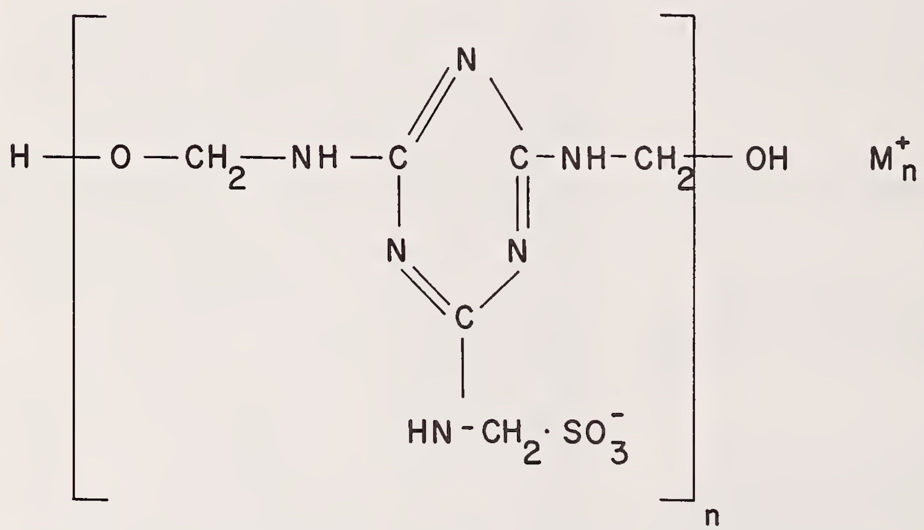

FIGURE 1B. SULFONATED MELAMINE-FORMALDEHYDE CONDENSATION PRODUCT

FIGURE 1. CHEMICAL STRUCTURES OF SUPER-WATER REDUCERS

TABLE 1

Summary Information on SWR Used in This Study

SWR	Manufacturer	Generic Class
Mighty-150	ICI, U.S., Inc.	Sulfonated naphthalene-formaldehyde condensate
Lomar D	Diamond Shamrock Corporation	Sulfonated naphthalene-formaldehyde condensate
Sikament	Sika Chemical Corporation	Sulfonated naphthalene-formaldehyde condensate
WRDA-19	W. R. Grace and Company	Sulfonated naphthalene-formaldehyde condensate
Alkanol-CA	E.I. Dupont De Nemours and Co.	Complex alkylaryl sulfonate
Melment L-10	American Admixtures Corp.	Sulfonated melamine-formaldehyde condensate
FX-32C	Fox Industries	Mixture of sulfonated naphthalene and melamine-formaldehyde condensates

TABLE 2

Chemical Tests on Admixtures

	ADMIXTURE						
Test	Mighty-150	Lomar-D	FX-32C	Melment L-10	Sikament	Alkanol-CA	WRDA-19
pH	8.75	8.50	11.04	8.28	7.89	8.50	10.10
Cl^- (% in solution)	0.048	0.097	0.285	0.267	0.024	0.746	0.036
Alkali (% as Na_2O in solution)	5.4	6.2	6.0	3.1	0.1	4.9	6.2
$SO_4^=$ (% in solution)	0.49	3.66	2.82	1.67	0.25	0.65	2.23
S* (total % of solid admixture)	28.3	31.3	28.5	27.3	29.4	29.4	26.9

*Total sulfur comprises that contributed by soluble inorganic sulphate ions, and organic sulfonate groups bound to naphthalene and melamine.

by weight of cement). In these cases the admixtures Lomar D, FX-32C, and WRDA-19 may add 0.1-0.15 percent alkali to the cement, possibly raising the total alkali above the 0.60 percent limit which may have been specified.

2.3 Spectrophotometric Analyses of SWR

A description of the procedures, and detailed results of both Infrared (IR) and Ultraviolet (UV) spectral analyses are presented in Appendix A. The following conclusions were drawn from the analyses:

1. The infrared spectra verify the manufacturer's description of Mighty 150, Sikament, WRDA-19, and Lomar D as sulfonated naphthalene-formaldehyde condensates. Alkanol also falls into this category.

2. There are minor differences in the spectra of these naphthalene compounds. These could be due to differing molecular sizes, different substitutions on the naphthalene rings, or impurities in solution.

3. The admixtures contain both organically bound sulfate groups (sulfonated naphthalenes) and free sulfate ($SO_4^{=}$) ions.

4. The spectra obtained for Melment indicates it to be of the melamine class. The broader IR peaks indicate a higher molecular weight product.

5. FX-32C was found to be a blend of naphthalene and melamine types.

2.4 Physical Properties

The two physical properties determined were specific gravity and percent solids (Table 3). The percent solids represents both active ingredients and other compounds (sulfates, chlorides, dyes, or other impurities).

TABLE 3

Physical Properties of SWR

	Density (gm/cm^3)	Solids Content (percent by weight)
Mighty 150	1.21	42.5
Lomar D	1.19	34.0
Sikament	1.20	39.5
WRDA-19	1.22	43.6
Alkanol-CA	1.15	31.9
Melment L-10	1.12	21.0
FX-32C	1.23	39.7

3. Evaluation of Dosage Requirements and Slump Loss in Cement Pastes

3.1 Technique

In order to investigate the seven SWR chosen in this study in as wide a variety of cements as possible, the technique of mini-slump testing was chosen. This test, developed by Dr. David Kantro at the Portland Cement Association, has proven useful in studies of the interaction between cements and a wide variety of admixtures (1). The ability of this test to assess the relative workability of a very large number of cement/admixture combinations at reasonable cost and free of the influence of aggregates and other mix design factors led to its use in the initial phase of this program. A complete description of the test procedure and interpretation of results is given in Appendix B.

3.2 Determination of Dosage Requirements

3.2.1 Initial Screening Series

Six cements were chosen for the initial investigation. Their major compositional factors are given in Table 4. Three of these (21731, 21732, 21733) are contemporary (1977) plant ground cements. One cement, MCC-274 is a laboratory grind of a commercial clinker. Cement LTS-25 is a Type II cement produced about 35 years ago. It has a low sulfate (gypsum) content and a relatively low Blaine surface area. The sixth cement, MCC-287 was prepared by the intergrinding of sufficient gypsum with LTS-25 to bring the SO_3 content up to 3.0%.

The admixtures used fall into two groups. The first, designated "A" types, are the seven SWR described in Section 2. An additional admixture included, Mighty RD-2, is a retarding version of Mighty 150. The second consisted of conventional water reducers, designated "B" types. These were: Plastiment, Daratard HC, Pozzolith 100XR, and Daratard. The first is a sodium glucoheptonate type, the second is formulated from modified salts of hydroxylated carboxylic acids, the third is a corn syrup, and the last a calcium lignosulfonate. In most cases, the admixtures were added to the initial mix water. In some instances, termed "delayed additions," the admixtures were added at the beginning of the second mix cycle.

The complete set of results is presented in Tables 84 and 85 (Appendix C). These data were constructed from plots of admixture dosage versus pat area (see Appendix B for a description of these procedures). Although the full set of plots is too voluminous to present in this report, typical plots showing the relative effectiveness of the seven SWR for three of the cements are shown in Figures 2-4. By inspection of these figures and the tables in Appendix C some conclusions can be drawn. The seven SWR appear to separate out into three distinct groups with regards to their effectiveness as water reducers. The first group consists of Mighty 150, Lomar D, Sikament, and WRDA-19, all naphthalene type admixtures. The second consists of Melment L-10 and FX-32C, a melamine and melamine/naphthalene blend. The last admixture, Alkanol-CA, requires much higher dosages to achieve equal water reductions to the others, and in some cases such as with cement 21733 (Figure 3), a decrease in pat area with dosage is seen. Although the data lie fairly close together, some separation in the naphthalene types can be seen. WRDA-19

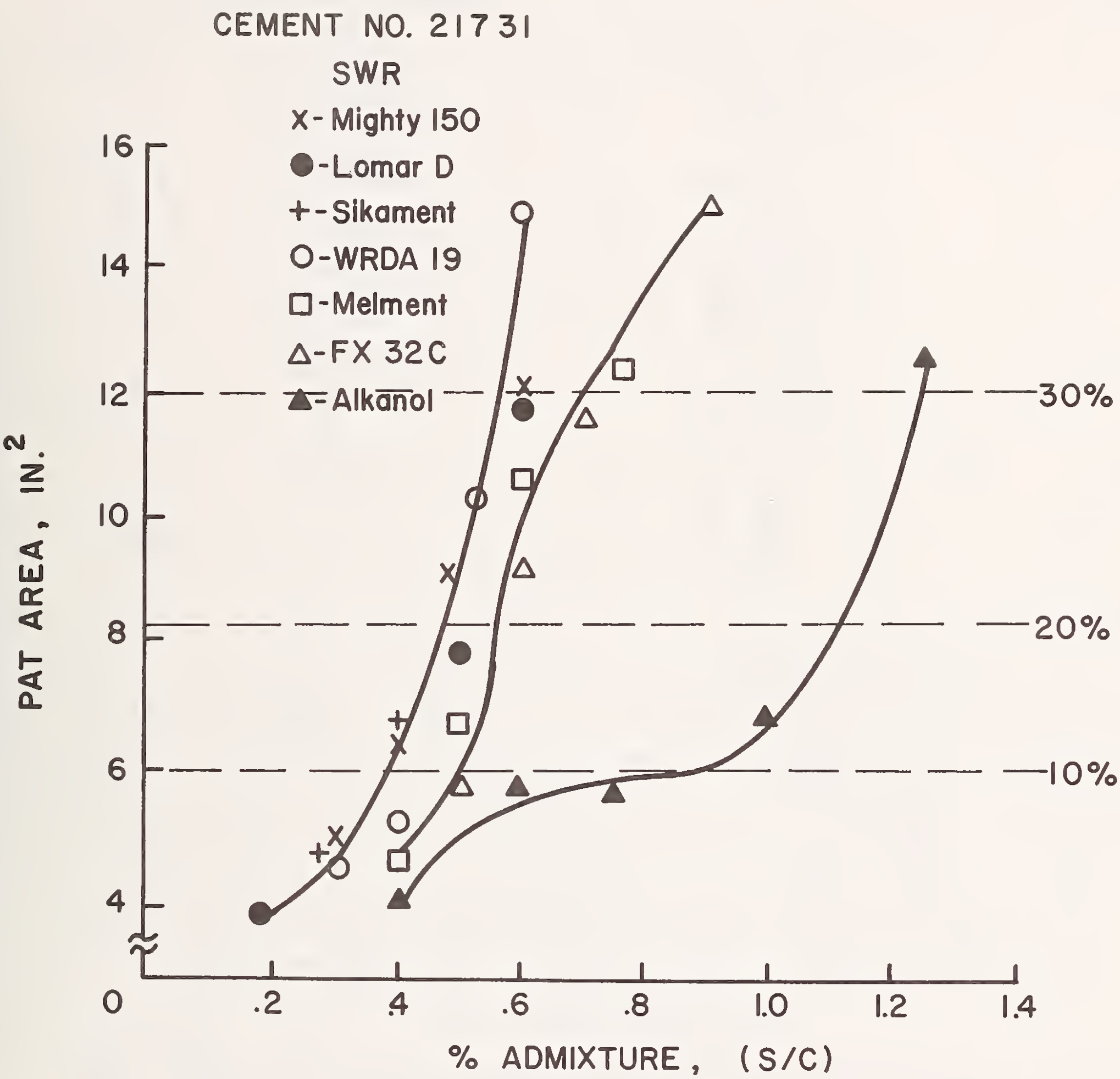

FIGURE 2. VARIATION OF PAT AREA WITH PERCENT ADMIXTURE

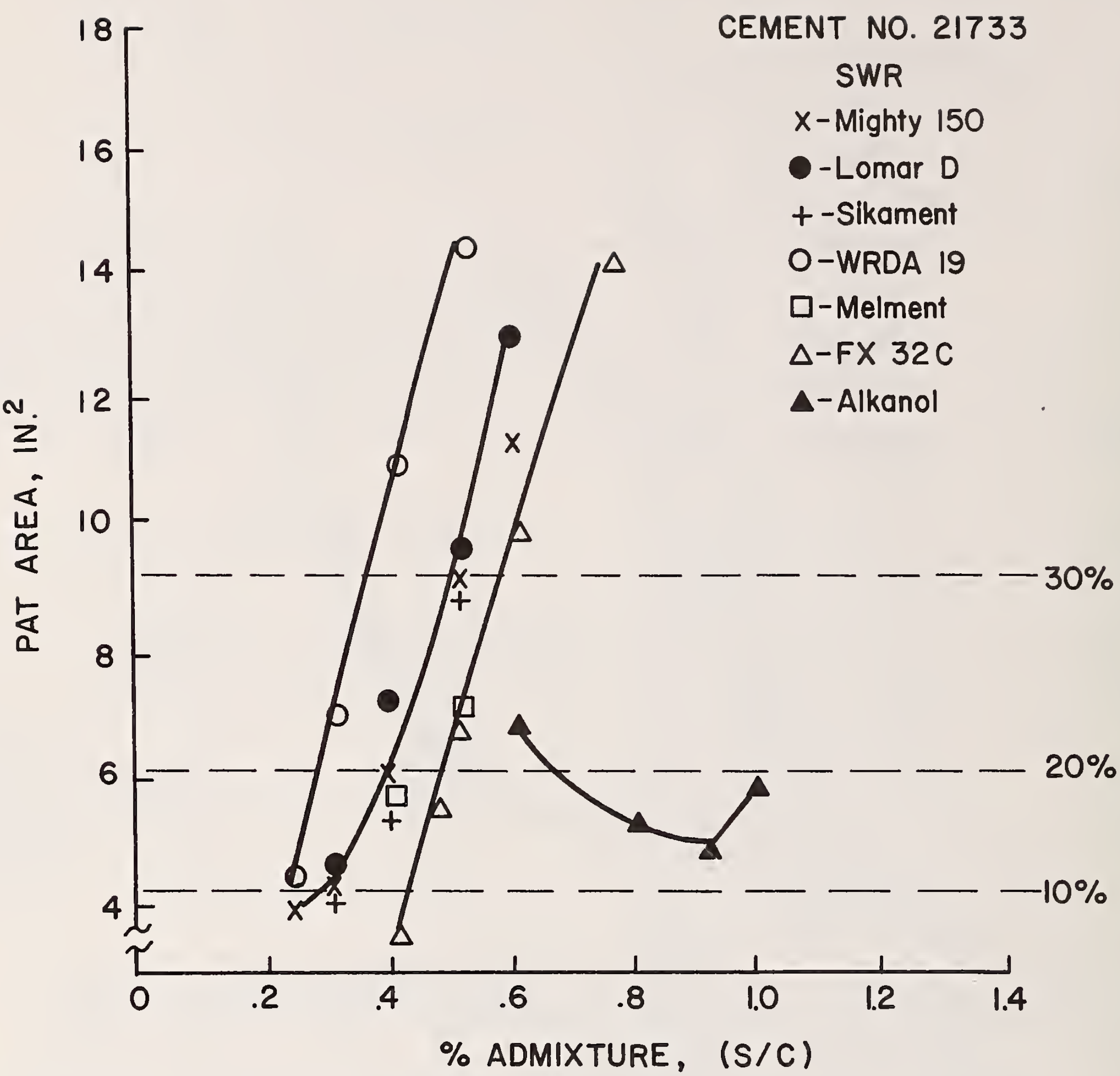

FIGURE 3. VARIATION OF PAT AREA WITH PERCENT ADMIXTURE

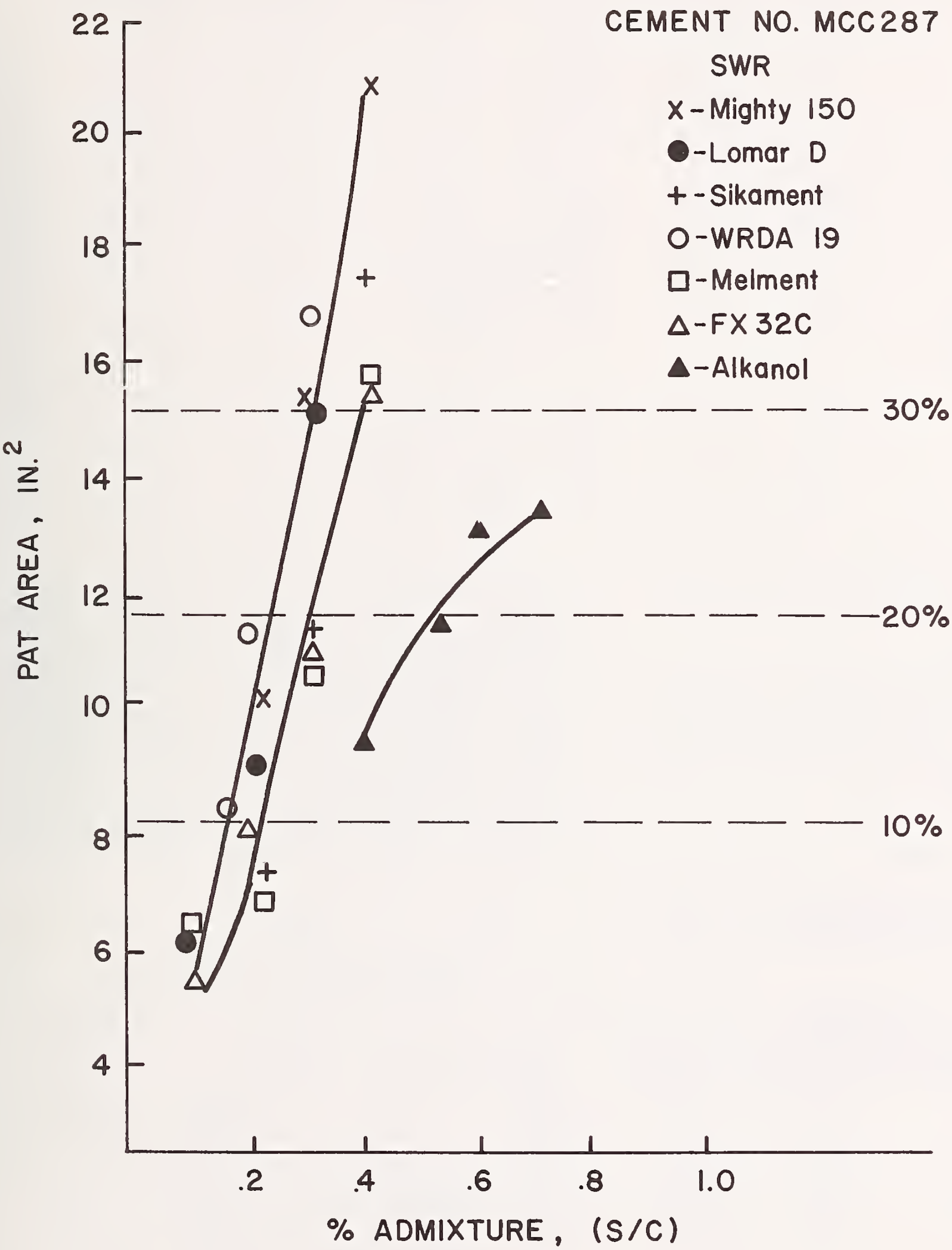

FIGURE 4. VARIATION OF PAT AREA WITH PERCENT ADMIXTURE

TABLE 4

Compositions of Cements

	Lot No.					
	21731	21732	21733	MCC-274	LTS-25	MCC-287
SiO_2	20.5	20.9	21.7	21.5	22.6	22.1
Al_2O_3	5.0	4.9	4.5	4.4	4.6	4.5
Fe_2O_3	2.5	3.1	2.6	3.0	4.9	4.8
CaO	63.4	63.8	63.0	62.5	61.9	60.4
MgO	2.7	2.0	3.1	2.8	2.2	2.1
SO_3	2.8	2.6	3.0	2.1	1.9	3.0
Na_2O	0.13	0.17	0.07	0.08	0.21	0.21
K_2O	0.99	0.66	1.00	0.38	0.54	0.53
Surface area, cm^2/g (Blaine)	3738	3513	3986	3440	3287	3480
C_3S	65.1	63.5	57.5	57.3	34.0	33.2
C_2S	9.7	12.0	18.8	18.4	39.0	38.1
C_3A	9.0	7.7	7.5	6.6	4.7	4.6
C_4AF	7.6	9.4	7.9	9.1	14.9	14.5

appears the most effective, with Mighty 150 and Lomar D yielding essentially identical results.

In order to afford the reader a concise summary of these findings, the following table shows the average dosage requirements for 20 percent water reduction for the three groupings.

TABLE 5

Average Dosage Requirement for Three Main SWR Groupings

	Groupings		
Cement	Naphthalene	Melamine	Alkanol
	Admixture Dosage Requirement (% s/c)		
21731	0.47	0.53	1.10
21732	0.37	0.50	0.56
21733	0.38	0.43	0.99
MCC-274	0.25	0.32	0.40
LTS-25	0.29	0.36	0.46
MCC-287	0.27	0.31	0.51

3.2.2 Effect of Delayed Addition

It has previously been shown (2) that the time-of-addition of water-reducing and retarding admixtures can have a great effect on their effectiveness and behavior in concrete mixtures. In most cases, a delay of a few minutes can increase the effectiveness of ordinary water-reducers, that is, less water-reducer need be added to obtain the same slump. In the "mini slump" test, any effect of delayed addition will manifest itself as an increase in pat area at equal w/c ratio. Some results obtained by delaying the addition of SWR until the second mix cycle (2-3-2) are shown in the following table. The

TABLE 6

Effect of Delayed Addition

Cement (Lot No.)	SWR	Dosage* % (s/c)	Pat Area Ratio (Delayed/ Initial Addition)
21731	Lomar D	0.40	3.3
	Melment L-10	0.50*	1.8
LTS-25	Lomar D	0.35	2.7
	Mighty 150*	0.25	2.1
	Sikament*	0.25	2.3
	WRDA-19*	0.25	2.1
	Alkanol	0.60	1.5

*For these mixes delayed mix was 0.5 lower in w/c ratio.

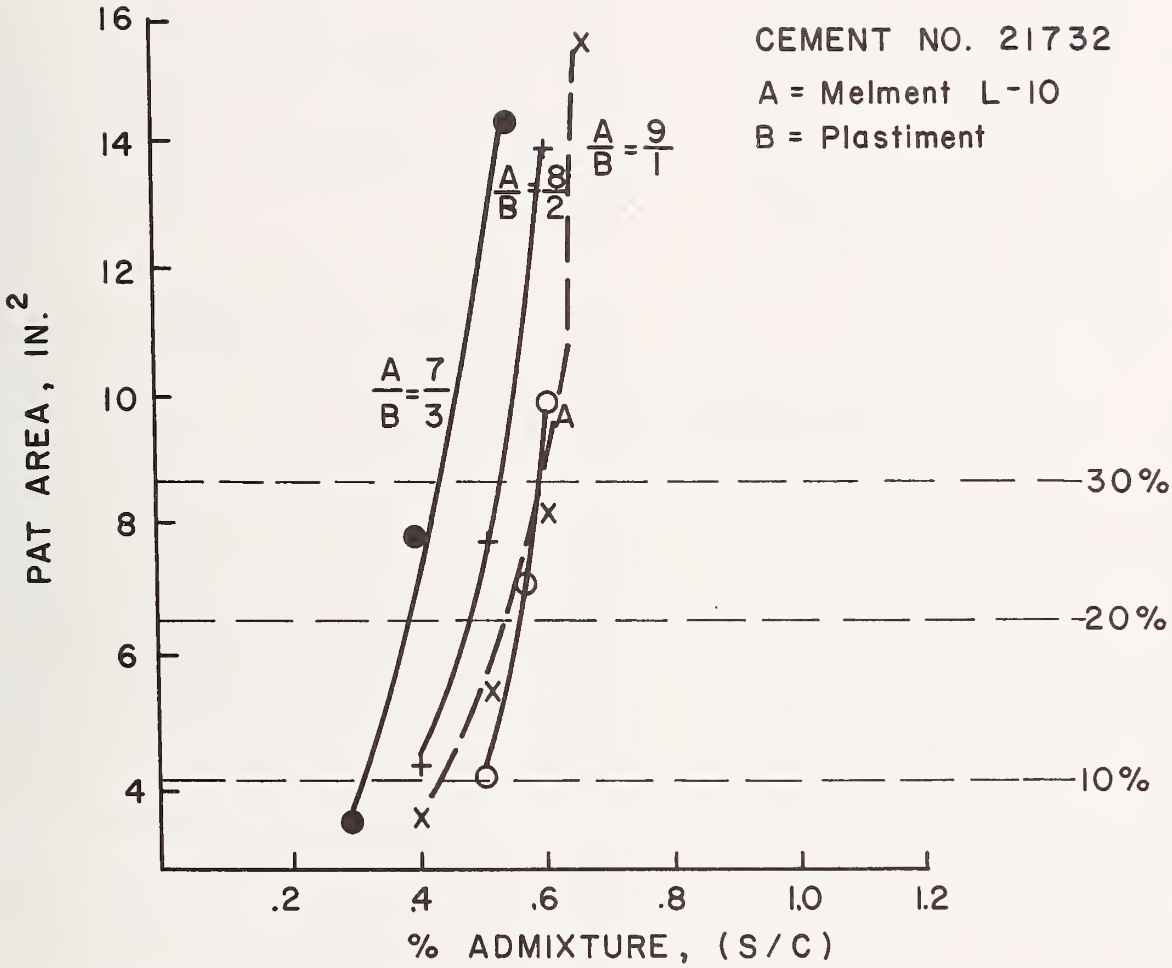

FIGURE 5. VARIATION OF PAT AREA WITH PERCENT OF BINARY ADMIXTURE

area ratio is obtained by dividing the pat area obtained from the delayed mix by the pat area obtained from the standard mix (SWR added with mix water).

Unfortunately, some of the delayed mixes had to be prepared at somewhat lower w/c ratios due to testing limitations. Thus, those data marked with an asterix (*) are on the conservative side. That is, if delayed pastes had been prepared at the same w/c ratio as the initial addition mix, the pat area ratio would have been larger. In any case, the expected effect is seen, a higher pat area occurring in those pastes where addition of the admixture was delayed by five minutes.

3.2.3 Binary Admixtures

Tables 84-85 (Appendix C) indicate that Type B admixtures, in themselves, are capable of achieving water reductions equal to those of the SWR, and at somewhat lower dosages. It is known, however, that addition of conventional water reducers at such high dosages will retard the hydration of portland cement to such an extent as to render the concrete useless for all practical purposes. It was thought that one could achieve both a cost savings and possibly a decrease in slump loss by using a blend of Type A (SWR) and Type B (conventional) products.

The complete set of data (expressed as percent of binary admixtures necessary to reduce water content 20 and 30 percent) are given in Tables 84-85 (Appendix C). An illustration of the effect of binary admixture dosages on pat area is shown in Figure 5. Here Plastiment (a sodium glucoheptonate) was blended with Melment L-10 (a melamine-based SWR) in proportions ranging from 9/1 (parts SWR/parts Plastiment) to 7/3. It is seen that as the percentage of Type B admixture in the blend is increased, the total amount of blended admixture needed to obtain a given pat area decreases. In this instance, the Type B admixture replaces more than its equivalent in SWR. This is not always the case, however, as can be seen from Table 7. Here the effects of various Type B admixtures on a single SWR in two cements are compared.

While the Plastiment additions lower the effective dosages in the high C_3A cement, the actions of the other Type B admixtures are more complex. In the low C_3A cement none of the Type B admixtures appreciably lower the admixture dosage necessary to achieve 20 percent water reduction.

The other SWR were tested in combination with Plastiment only. Amounts required for 20 percent water reduction are shown in Table 8. Again, in the higher C_3A cement an increase in the percentage of Plastiment in the blend allows for a reduction in total admixture dosage. For the lower C_3A cement, in most cases, no consistent effect of Plastiment substitution was seen.

3.2.4 Further Work - Effects of Chemical Composition on Dosage Requirements

The initial screening series indicated that cement characteristics have a great influence on SWR dosage requirements. The data suggested that C_3A content, fineness, and possibly other parameters were influential. A more detailed investigation was, therefore, warranted, in which a large number of cements would be tested for dosage requirements using the "mini slump" procedure. Three SWR representative of the two major classes were chosen.

A suite of seventeen cements were used for this study (see Appendix D). Many of them had been used in previous studies of cement/admixture interactions, others were received during the course of this project and used in various phases of the concrete work (described in later sections). The majority were contemporary plant ground cements, available on the open market. These were preferred to laboratory research cements for the purpose of this study; although the latter might have allowed more definitive correlations between compositional parameters and SWR dosage to be drawn, the use of commercial cements allowed us to gain a feel for the actual variation a user of these SWR would encounter in practice between various cement brands.

3.2.4.1 Effect of C_3A (Tri-calcium Aluminate) Content

Much of the literature data in the admixture field (3,4,5) indicate that dosage requirements for conventional water-reducers are dependent on tricalcium aluminate (C_3A) content of the cement, higher C_3A cements usually requiring more water-reducer to reach a given level of water reduction. While many studies utilized potential C_3A composition as a parameter, it is now recognized that this is, in most cases, an over-estimation of the true C_3A content of the cement. Distribution of aluminates into the silica phase (6) results in a lowering of the C_3A content under actual kiln conditions. In the present study, quantitative x-ray diffraction (XRD) procedures were used to determine the actual C_3A contents. These are presented in Appendix D along with potential compound compositions. The equipment and techniques used in the

TABLE 7

Effect of Type B Admixtures on Dosage Requirements for Two Cements

SWR	Type B	Ratio A/B	Cement 21731 (C_3A = 9.0) Dosage (% s/c)	Cement MCC-287 (C_3A = 4.6) Dosage (% s/c)
Lomar D	Plastiment	9/1	0.47	0.27
		8/2	0.40	0.28
		7/3	0.35	0.26
	Pozzolith 100XR	9/1	0.48	0.28
		8/2	0.50	0.28
		7/3	0.47	0.26
	Daratard	9/1	0.47	0.25
		8/2	0.49	0.25
		7/3	0.50	0.27
	None		0.50	0.26

TABLE 8

Effect of SWR on Dosage Requirements of Two Cements
Using a Single Type B Admixture

Type B	SWR	Ratio A/B	Cement 21731 (C_3A = 9.0) Dosage (% s/c)	Cement MCC-287 (C_3A = 4.6) Dosage (% s/c)
Plastiment	Lomar D	10/0	0.50	0.26
		9/1	0.47	0.27
		8/2	0.40	0.28
		7/3	0.35	0.26
	Melment L-10	10/0	0.50	0.32
		9/1	0.63	0.31
		8/2	0.53	0.28
		7/3	0.35	0.25
	Mighty-150	10/0	0.47	0.23
		9/1	0.43	0.24
		8/2	0.40	0.24
		7/3	0.36	0.25
	FX-32C	10/0	0.55	0.30
		9/1	0.51	0.30
		8/2	0.49	0.29
		7/3	0.38	0.31
	Sikament	10/0	0.44	0.31
		9/1	0.46	0.27
		8/2	0.42	0.24
		7/3	0.35	0.19

XRD determinations are fully described in an earlier publication (7).

Relationships between C_3A content (XRD) and admixture dosage necessary to achieve 30 percent water reduction are shown in Figures 6A-C for Mighty 150, Lomar D, and Melment L-10. The plots clearly show a relationship between C_3A content and SWR requirement. The fact that the intercept at zero C_3A content is not zero indicates that admixture is being

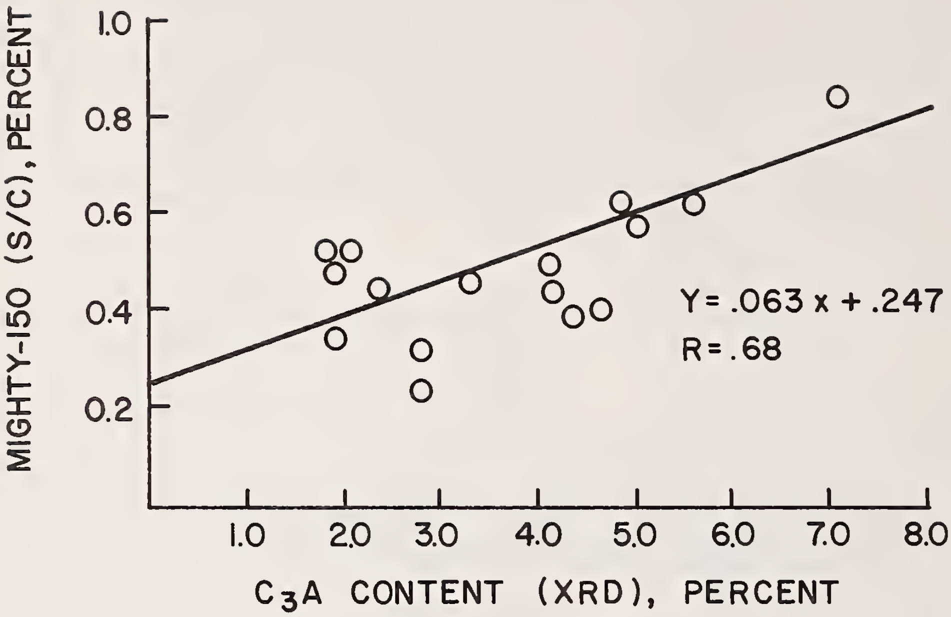

FIGURE 6A. MIGHTY-150

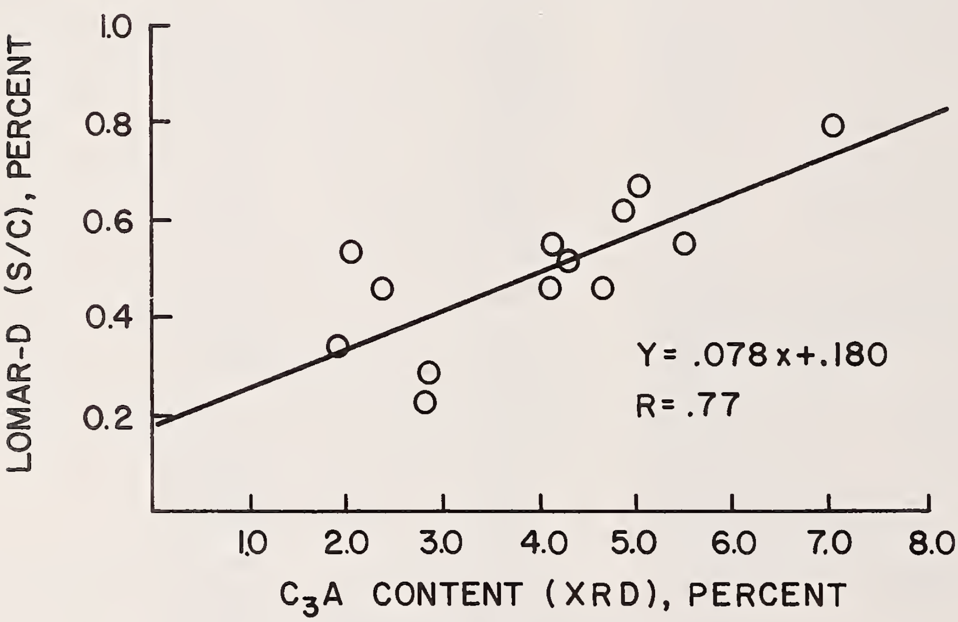

FIGURE 6B. LOMAR-D

FIGURE 6. DOSAGE REQUIREMENTS OF SWR AS A FUNCTION OF C_3A CONTENT

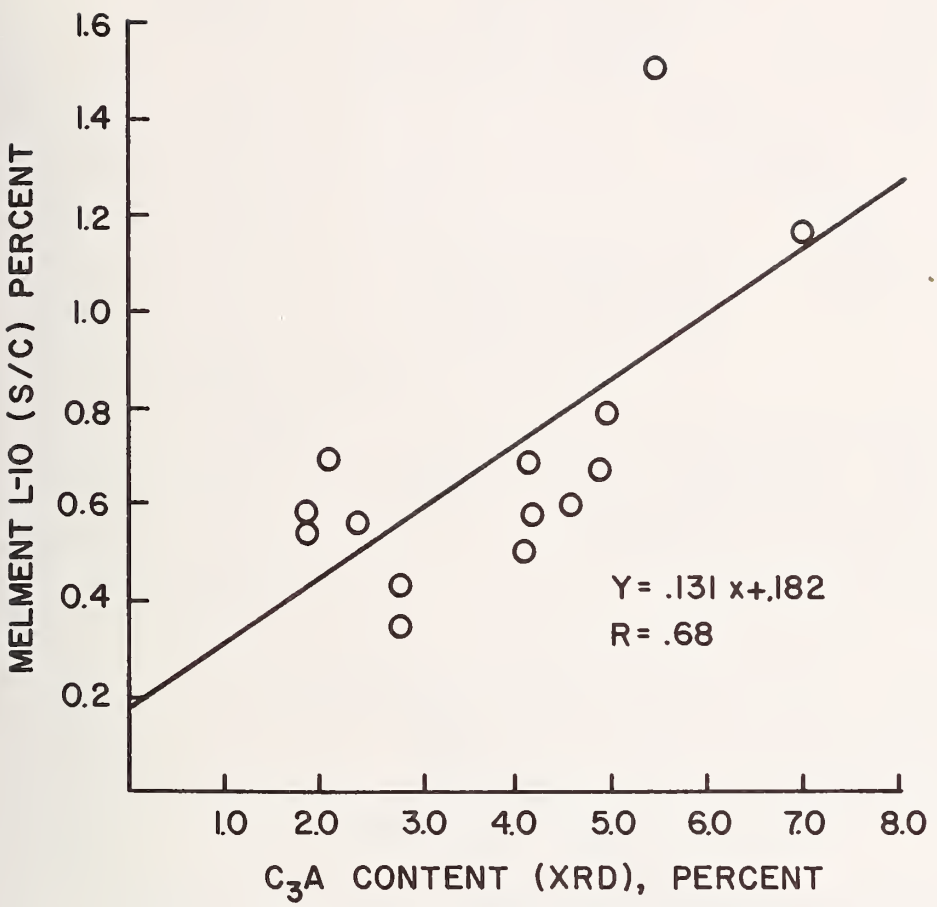

FIGURE 6C. MELMENT L-10

FIGURE 6 (CON'T). DOSAGE REQUIREMENTS OF SWR AS A FUNCTION OF C_3A CONTENT

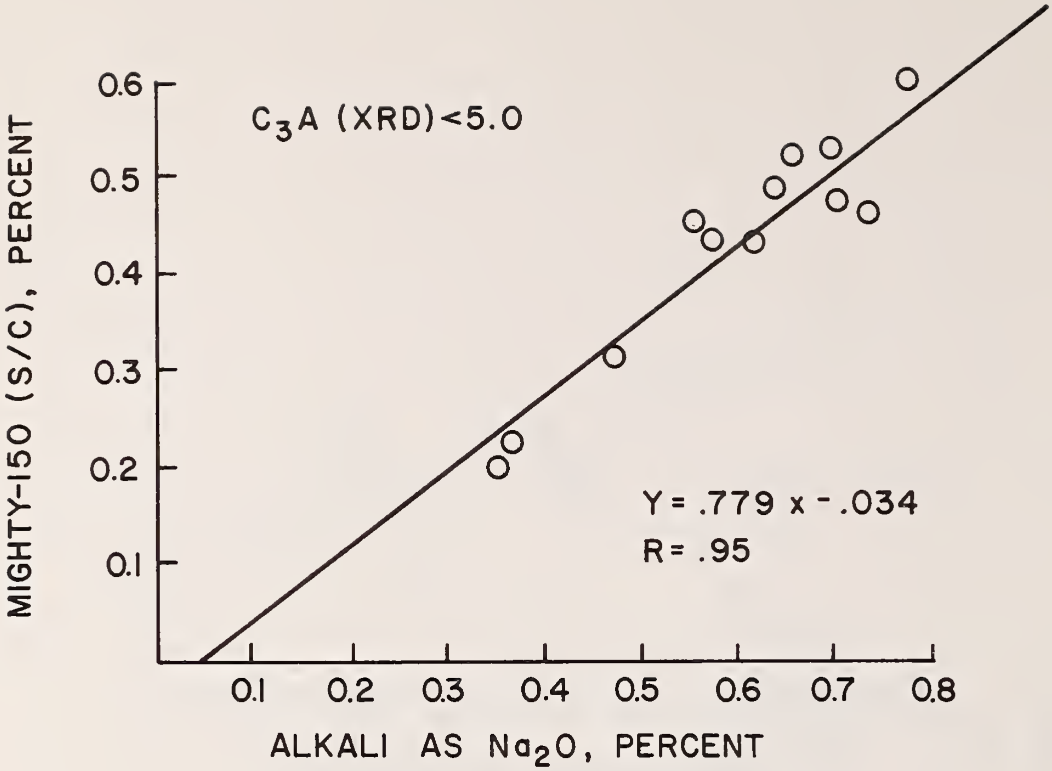

FIGURE 7A. MIGHTY 150

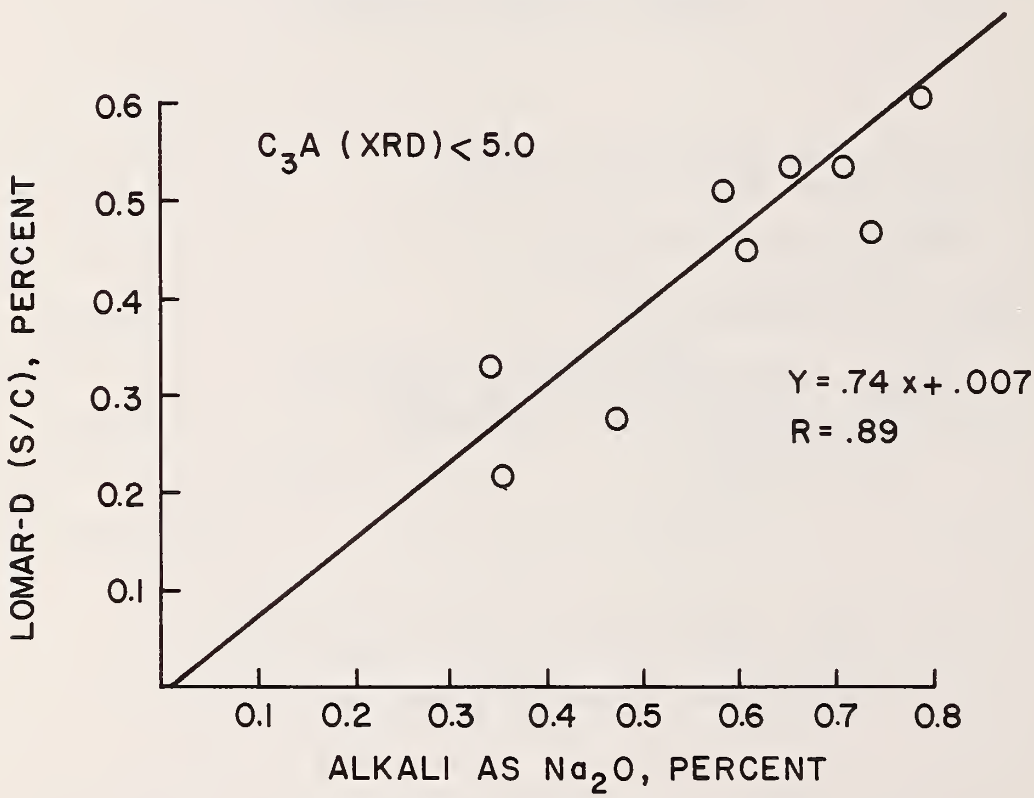

FIGURE 7B. LOMAR D

FIGURE 7. DOSAGE REQUIREMENTS OF SWR AS A FUNCTION OF ALKALI CONTENT

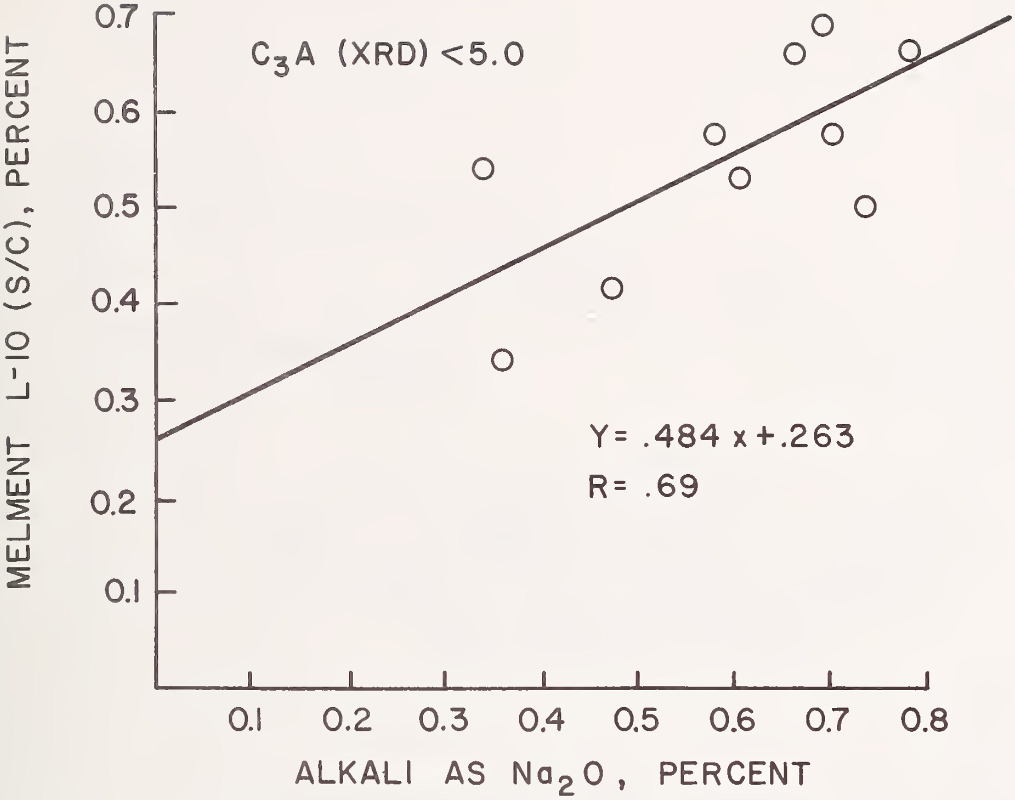

FIGURE 7C. MELMENT L-10

FIGURE 7 (CON'T). DOSAGE REQUIREMENTS OF SWR AS A FUNCTION OF ALKALI CONTENT

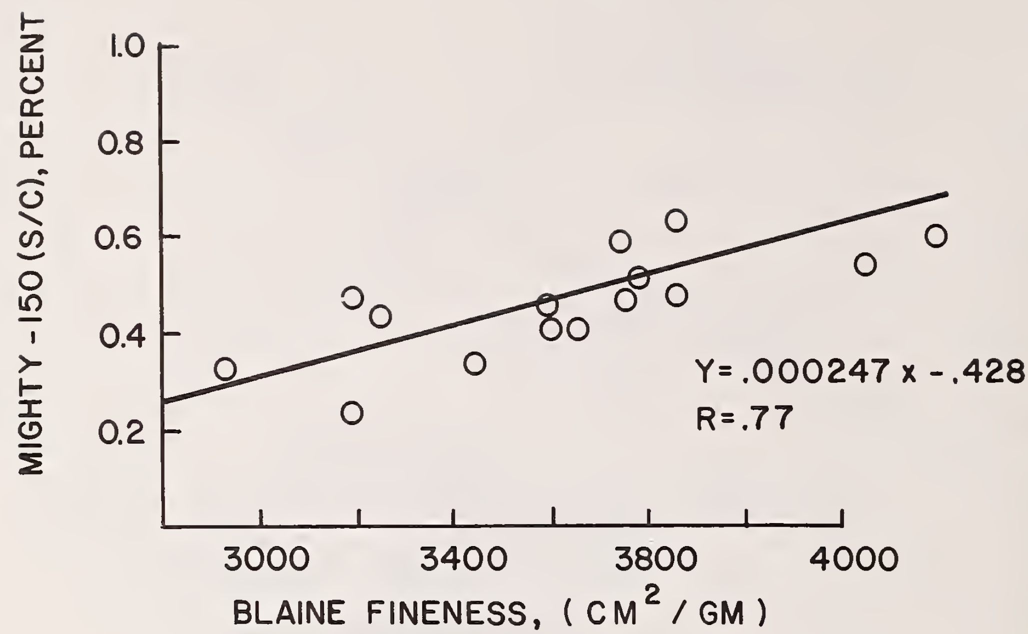

FIGURE 8A. MIGHTY - 150

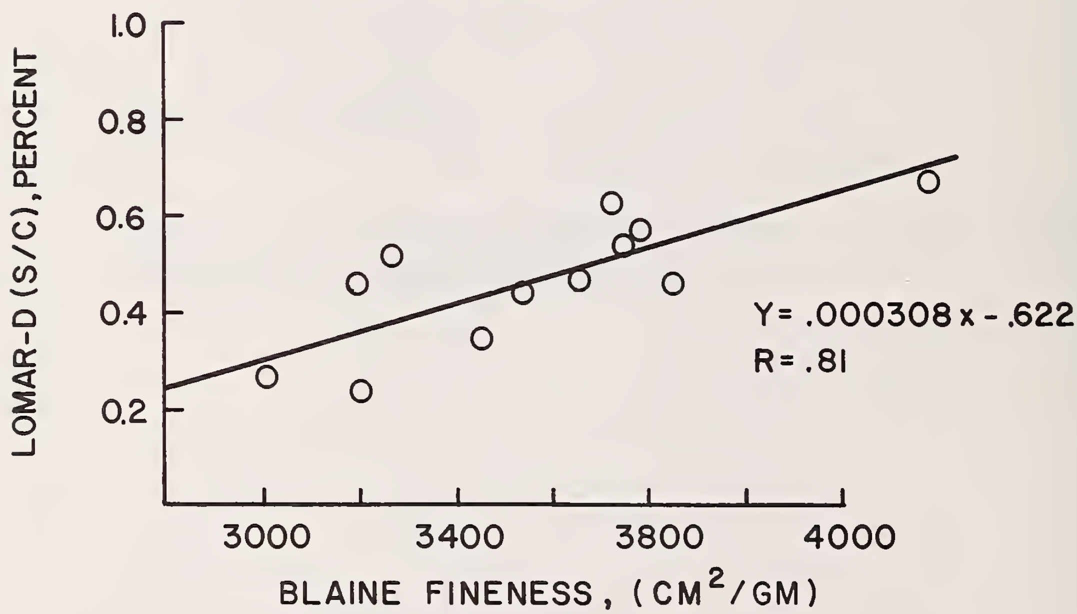

FIGURE 8B. LOMAR - D

FIGURE 8. DOSAGE REQUIREMENTS OF SWR AS A FUNCTION OF BLAINE FINENESS

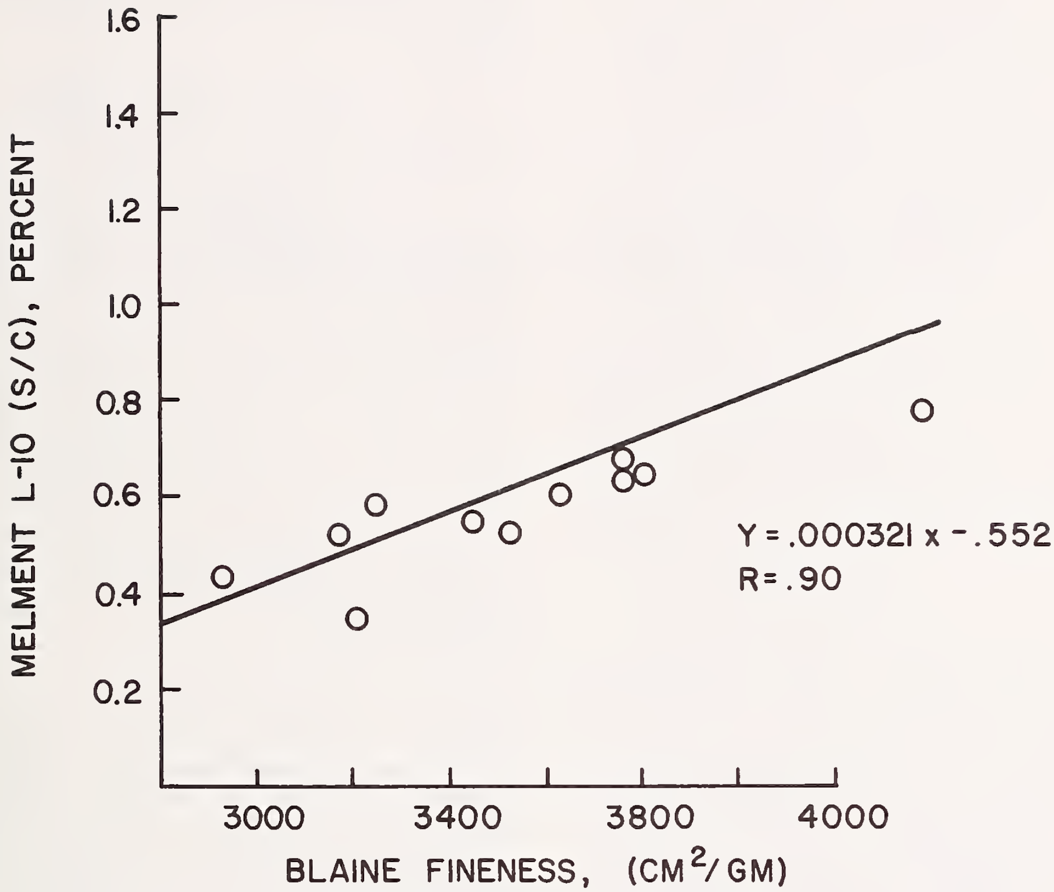

FIGURE 8C. MELMENT L-10

FIGURE 8. DOSAGE REQUIREMENTS OF SWR AS A FUNCTION OF BLAINE FINENESS

adsorbed onto other cement compounds, most likely silicates. A mini slump series performed on Tamm Quartz (pure SiO_2) indicated maximum pat area at 0.2% M-150, similar to the resulting intercept at zero C_3A content. Therefore, we may say that the lower bound for admixture requirement is approximately 0.2% by weight at zero C_3A. An increase in C_3A raises the requirement. This increase is proportional to the slopes of the regression lines drawn through the data. An average slope of about 0.07% SWR per unit increase in C_3A is seen for the naphthalene, and 0.13% SWR per unit increase in C_3A is seen for the melamine. Expressing this in terms of the admixture requirement for zero C_3A, one would need almost twice as much SWR at C_3A contents of 2.0-3.0 percent, and almost 3 times as much SWR at C_3A controls of 5.0 to 6.0 percent for the naphthalenes, and considerably more for the melamines. This has obvious economic implications, although the difficulties in translating mini slump data into dosage amounts for concrete, and the expense of obtaining XRD data on a particular cement does not allow one to use these data for purposes of cost analysis.

3.2.4.2 Effect of Alkali Content

The relatively low correlation coefficients in Figure 6A-C indicate parameters other than C_3A content may be influencing the admixture demand. This is especially apparent below about 5.0 percent C_3A where the scatter is highest. Bruere (8) has noted that alkali content can have a significant effect on cement/admixture interactions. The relationships between alkali content (expressed as equivalent Na_2O) and percentage SWR needed for 30 percent water reduction are shown in Figures 7A-C for Mighty 150, Lomar D, and Melment L-10. For the naphthalene SWR, the relationship is very strong, for the melamine the relation exhibits essentially the same correlation coefficient as for C_3A (Figure 6C).

In general, data below 0.60 percent total alkali ("low alkali" cements) also correspond to cements with low XRD C_3A contents. Therefore, in this region it is unclear whether C_3A, alkali, or a combination of the two is exerting more of an influence on the admixture requirement. Above 0.60 percent total alkali, the SWR dosage increase even though C_3A fluctuates widely. In this region, obviously, alkali is the dominant factor (provided C_3A is less than 5.0 percent). Above 5.0 percent C_3A, alkali content is less important, the aluminate being the decisive parameter in this region.

In practice, it would be easier to obtain a cement lower in C_3A then one lower in alkalies. Due to the introduction of preheater systems and restrictions on stack emissions, alkali contents of cements, in general, are on the increase. In many localities it may not be possible to obtain low alkali cement, this is especially true in the eastern U.S. For these reasons, the applications of these data by the potential user of SWR is limited.

3.2.4.3 Effect of Cement Fineness

One might expect an increase in cement fineness to lead to an increase in admixture dosage requirement, as more surface area for adsorption of the admixture would become available. This was seen for the particular admixtures and cements used in this study (Figures 8A-C). Relationships were fairly good, highest correlation between fineness and admixture demand being seen in the case of Melment L-10. The cements having highest C_3A content were excluded from these data sets, so as not to bias the results. Unfortunately, some of the higher fineness cements were also those having high alkali contents, therefore, it is difficult to separate these two variables as to their separate effects on SWR dosage requirements.

3.2.4.4 Effect of Sulfates

Almost all of the cement included in the study had sulfate contents in the typical range of 2.0 to 3.0 percent. This is typical of commercial cements, and the relatively narrow range of values makes it difficult to detect any influence of sulfate content on the SWR dosage requirements.

Evidence for the effect of sulfate composition is obtained from the behavior of Cement 21785. When first tested for admixture requirement, an unusually high value of 1.05% Mighty-150 (by solids) was obtained for 30% water reduction. In this cement it was found from x-ray studies that almost all the sulfate was present as anhydrite ($CaSO_4$). Anhydrite is less soluble than gypsum ($CaSO_4 \cdot 2H_2O$) and less sulfate will be available during the initial stages of hydration. Thus, the C_3A will be more able to take up admixture onto its surfaces, as the C_3A will not have reacted with $SO_4^=$ to form ettringite.

When 1% additional SO_3 as plaster ($CaSO_4 \cdot 1/2H_2O$) is added to Cement 21785 the admixture requirement drops to 0.57% Mighty 150, indicating that sulfate phase composition indeed can have an effect on

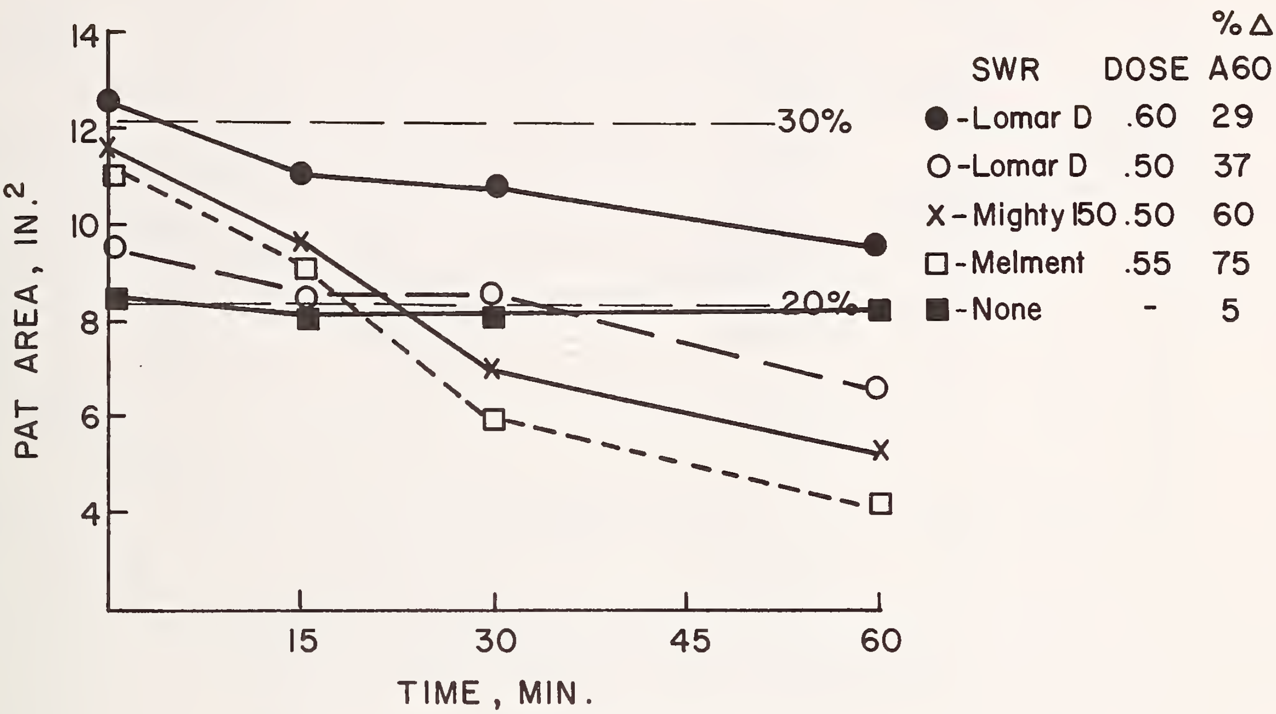

FIGURE 9A. CEMENT NO. 21731

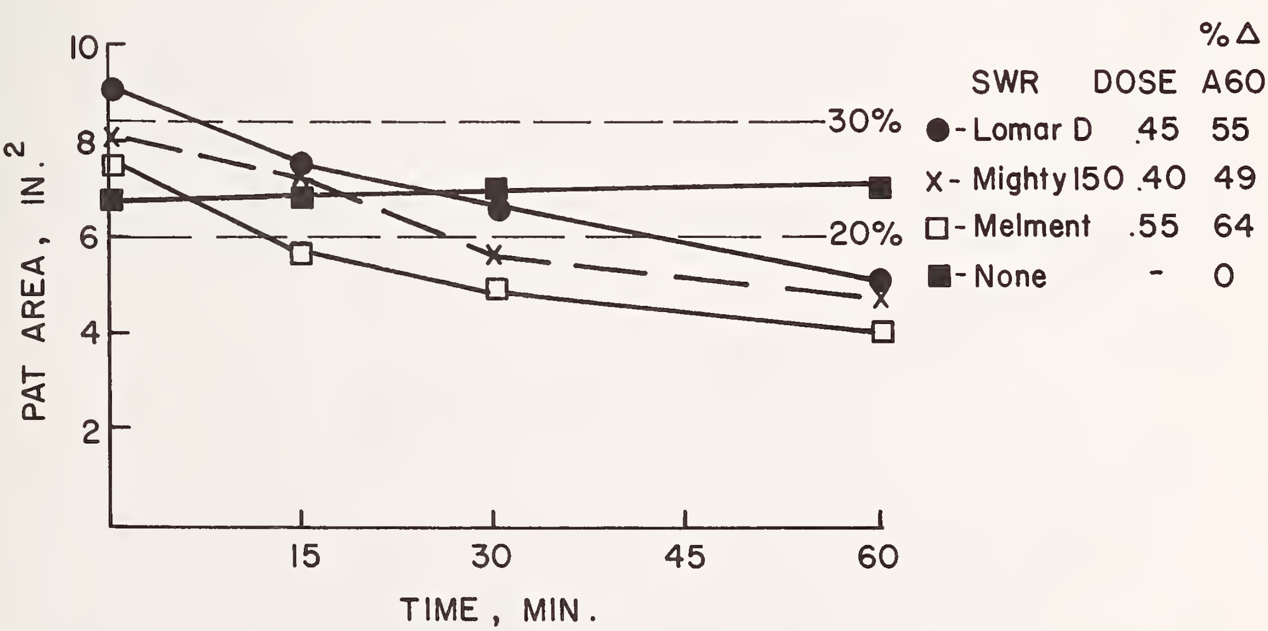

FIGURE 9B. CEMENT NO. 21732

FIGURE 9. PAT AREA VERSUS TIME FOR TWO CEMENTS

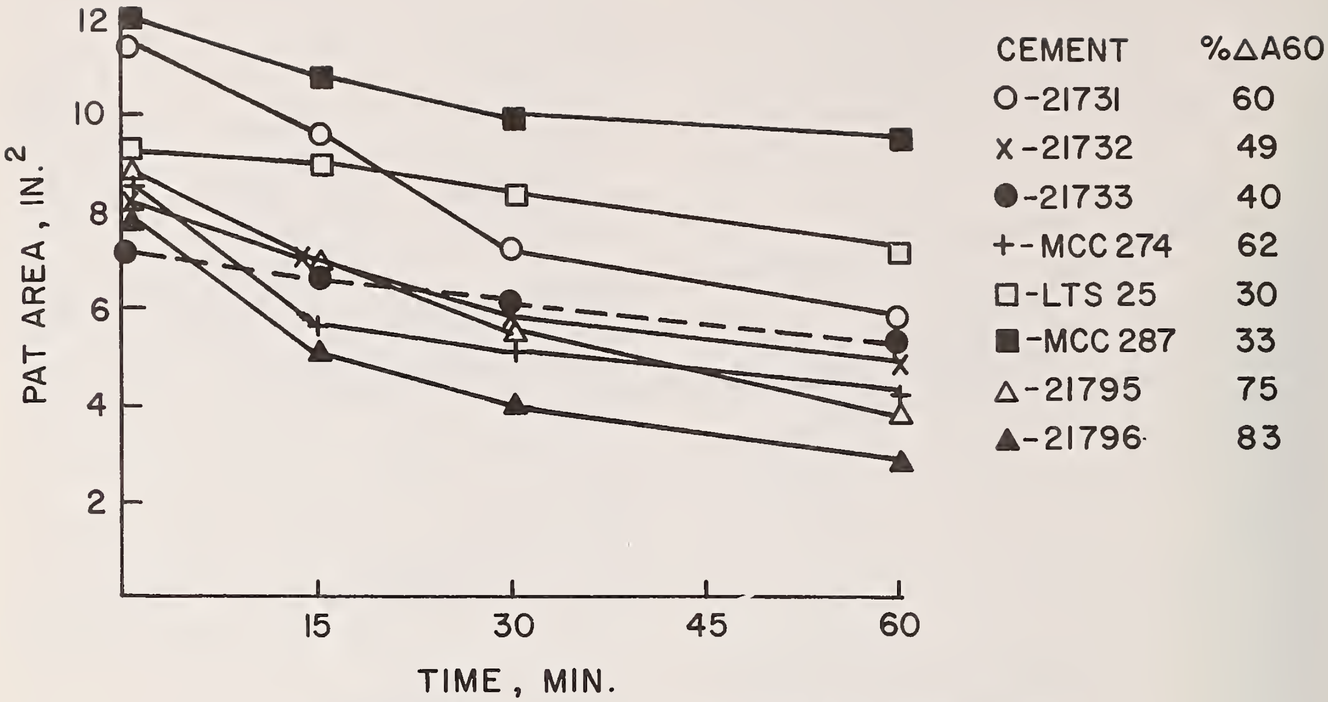

FIGURE 10A. MIGHTY-150 INITIAL ADDITION

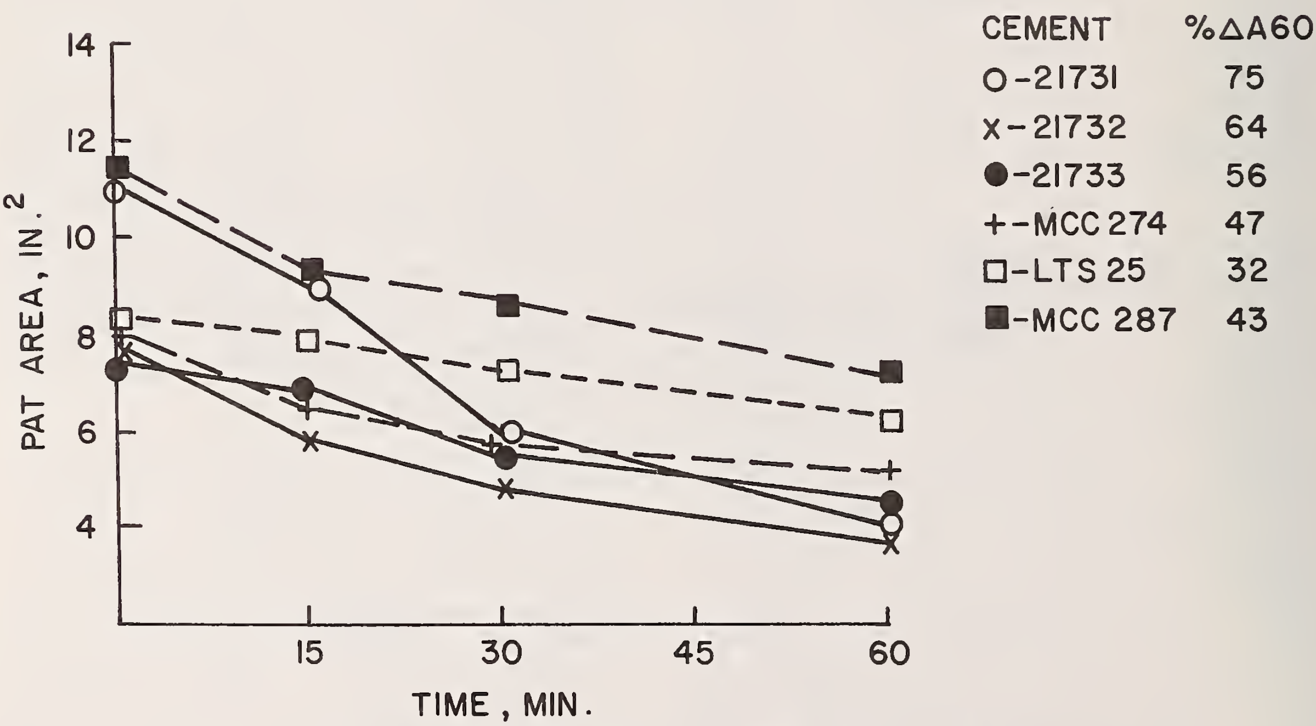

FIGURE 10B. MELMENT L 10 INITIAL ADDITION

FIGURE 10. PAT AREA VERSUS TIME FOR TWO SWR

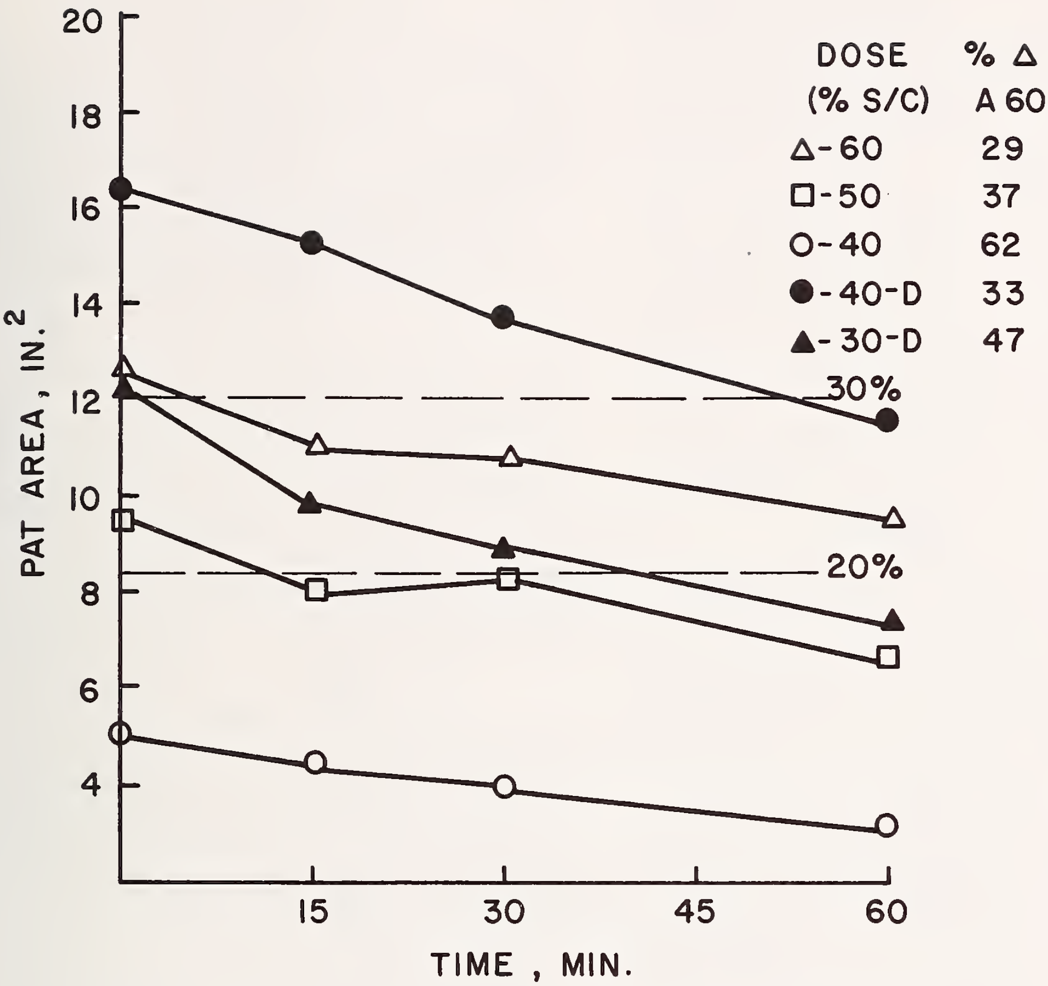

FIGURE 11. PAT AREA VERSUS TIME FOR CEMENT NO. 21731 WITH LOMAR-D

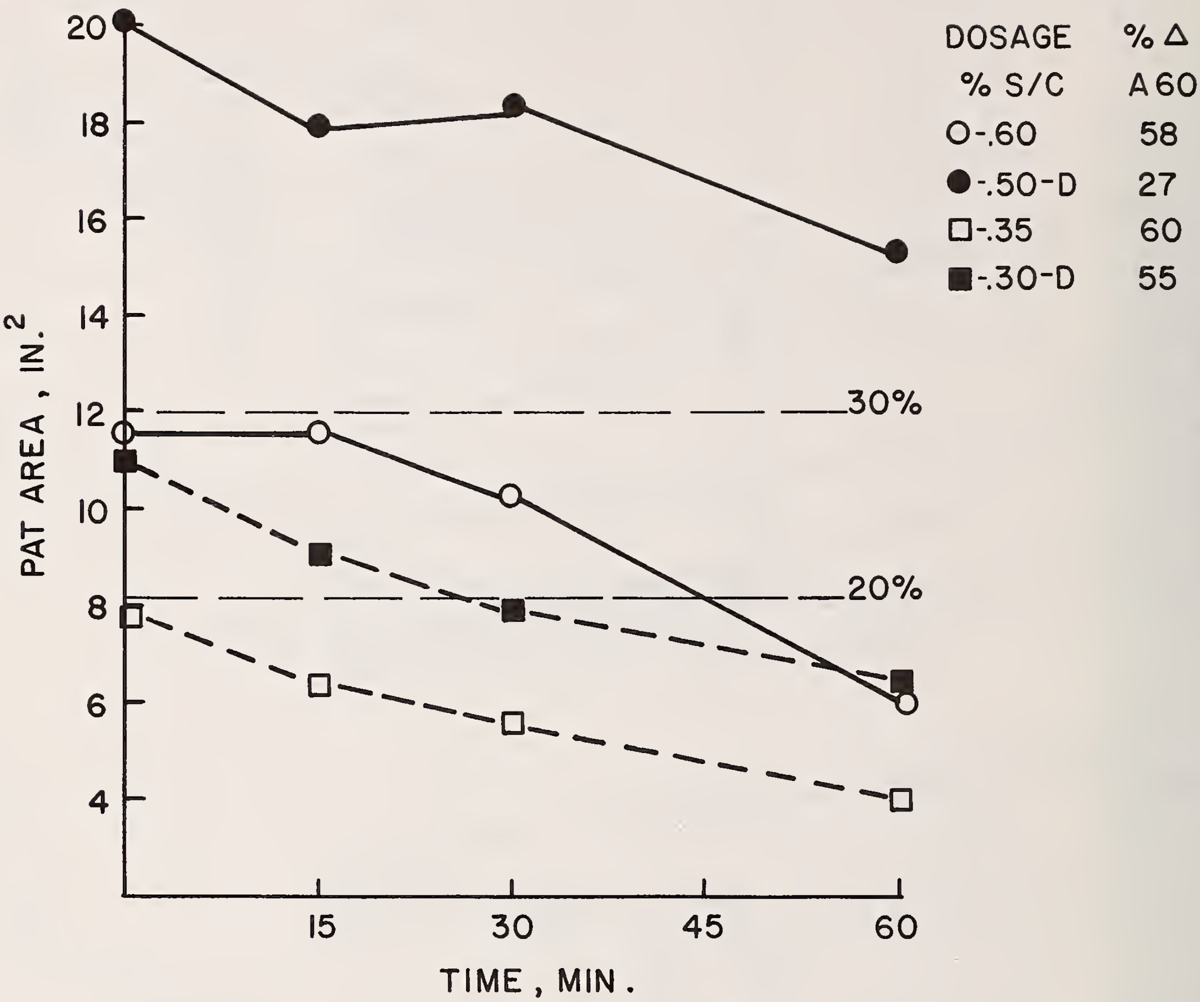

FIGURE 12. PAT AREA VERSUS TIME FOR CEMENT NO.21731 WITH MELMENT L-10

admixture dosage. The addition of plaster cannot be used in general to lower the admixture requirements of all cements. If the sulfate is initially in the gypsum phases (as is usually the case), the solution will initially be super-saturated and no benefits will be obtained by adding more sulfate to the cement.

3.3 Evaluation of Slump Loss

Pat area loss studies were performed on the seven SWR in combination with the six cements listed in Table 4. In addition to these cements, a limited amount of pat area loss tests were conducted on combinations of Mighty 150 and Cements 21795 and 21796 (See Appendix D), as these cements were later to be used in concrete mixtures. The testing was carried out using the techniques described in Appendix B.

Almost 200 pat area loss tests were performed in this phase of the study. The complete data are contained in Tables 86-91 of Appendix C. In the interests of conciseness, only a limited number of illustrative examples will be presented in the main body of this report. This will allow the reader to examine the most important trends which were derived from the longer, more complete body of data in the Appendix.

3.3.1 Initial Additions of SWR

The first series involved pat areas loss tests on cements to which the SWR were added in the initial mix water. Figures 9A and 9B compare pat area loss curves for a number of the SWR in combination with two cements having significant differences in admixture dosage necessary to reach a given water reduction. Also included in the figures are the percentage area losses during the 60 minutes of testing (% ΔA_{60}). For both cements, the area losses appear to be higher for the melamine based admixtures. Also, higher pat area losses are sustained when lower admixture dosages are used, although this may be related to the lower initial pat areas in these cases. The most dramatic observation, however, is the large difference in behavior between the control (no SWR) and the SWR mixes. The highest % ΔA_{60} encountered for the controls was 13.1% (Cement No. MCC-287), values for the majority of the controls were much lower. Although this could be simply an effect of the higher w/c ratio of the control mixes, the differences between the various SWR suggest chemical factors are operative. As controls prepared at the same w/c as the SWR mixes (w/c = 0.36) would be essentially "no-pat" pastes (analogous to "no-slump" concretes) a comparison at equal w/c ratio could not be made.

An illustration of the complexities of the relationship between cement composition and pat area loss can be seen in Figures 10A and B. Here pat area losses are plotted for Mighty 150 (Figure 10A) and Melment (Figure 10B) when combined with various cements. In general, the cements having highest values of C_3A, alkalies, and fineness show the largest pat area losses. There are exceptions, however, such as Cement 21796, which is low in C_3A, alkali, and fineness, yet shows a high pat area loss. A low dosage requirement does not necessarily translate into a low rate of pat area loss. For instance, Cement MCC-274 has the lowest dosage requirement for all of the cements tested (see Table 5), but shows a relatively high rate of pat area loss compared to many of the other cements used with Mighty 150, and two other cements used with Melment L-10. It is apparent that the relationship between cement composition and pat area loss is much more complicated than is the case for dosage requirements.

3.3.2 Delayed Additions of SWR

The utilization of delayed addition of SWR as a means of reducing the dosage requirement has already been discussed (Section 3.2.2). Delayed addition is also beneficial in reducing the rate of pat area loss. This is illustrated for a high C_3A content cement (No. 21731) in Figures 11 (Lomar D additions) and 12 (Melment L-10 additions). For the Lomar D, delay in addition cut pat area loss approximately in half at equivalent dosage. For the Melment case (Figure 12) a comparison at equivalent dosage was not available, but delayed additions resulted in lower pat area losses than initial additions run at somewhat higher dosages, indicating that if delayed additions had been made at equivalent dosages, even greater reductions in pat area loss would have been seen. When delayed addition is used to achieve equivalent initial pat area, however, the rate of loss is greater in the delayed case. This can also be seen in Figure 11, compare the case where 0.60 percent Lomar D was used (initial area = 12.5) versus the case where 0.30 percent Lomar D was used in delayed mode (initial area = 12.4). The latter has a higher area loss rate. In the Melment case (Figure 12) the pat area loss rates of pastes prepared at equal initial areas with and without delay were essentially equal.

Similar effects can be seen for a low C_3A, low alkali cement (LTS-25),

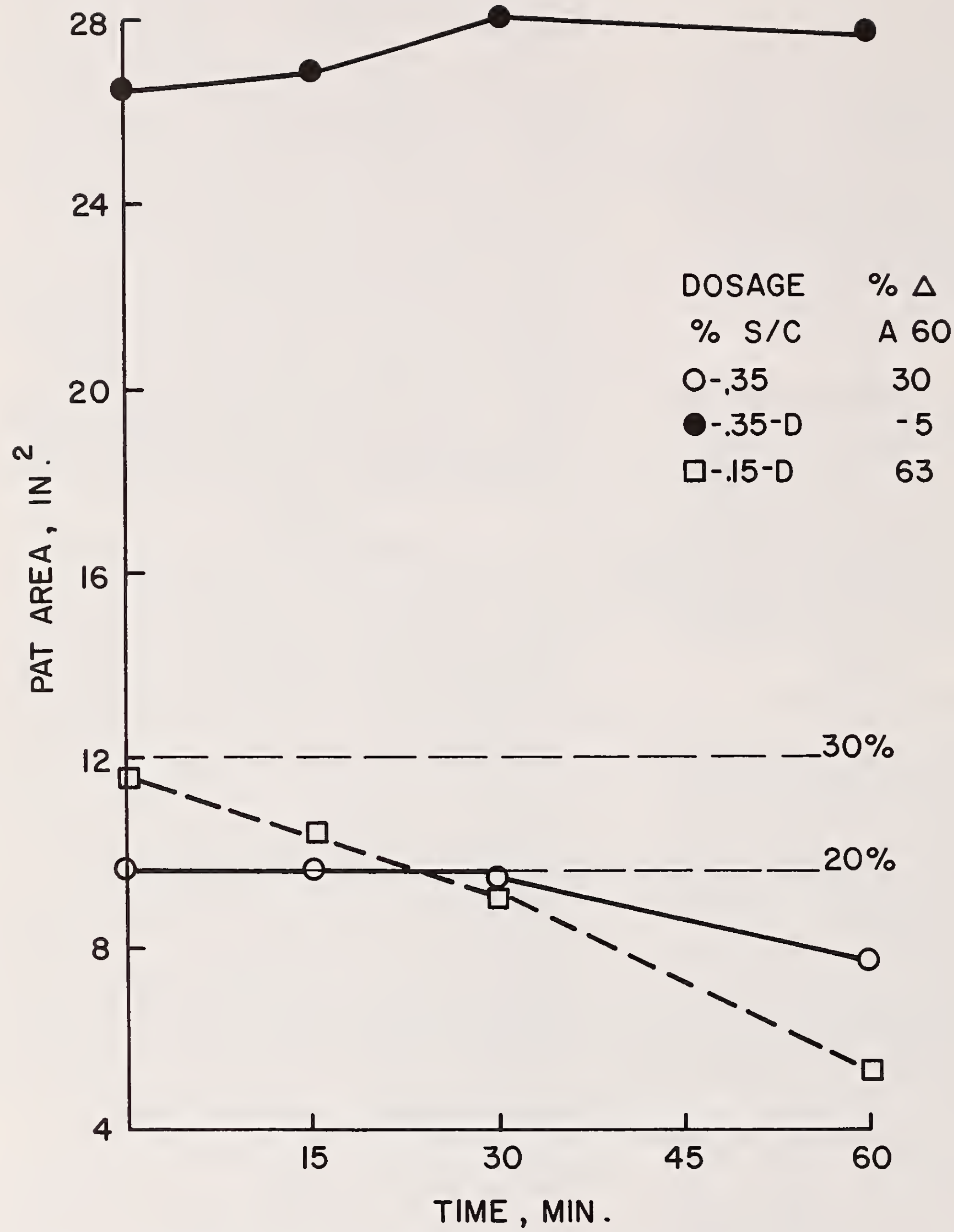

FIGURE 13. PAT AREA VERSUS TIME FOR CEMENT NO. LTS-25 WITH LOMAR-D

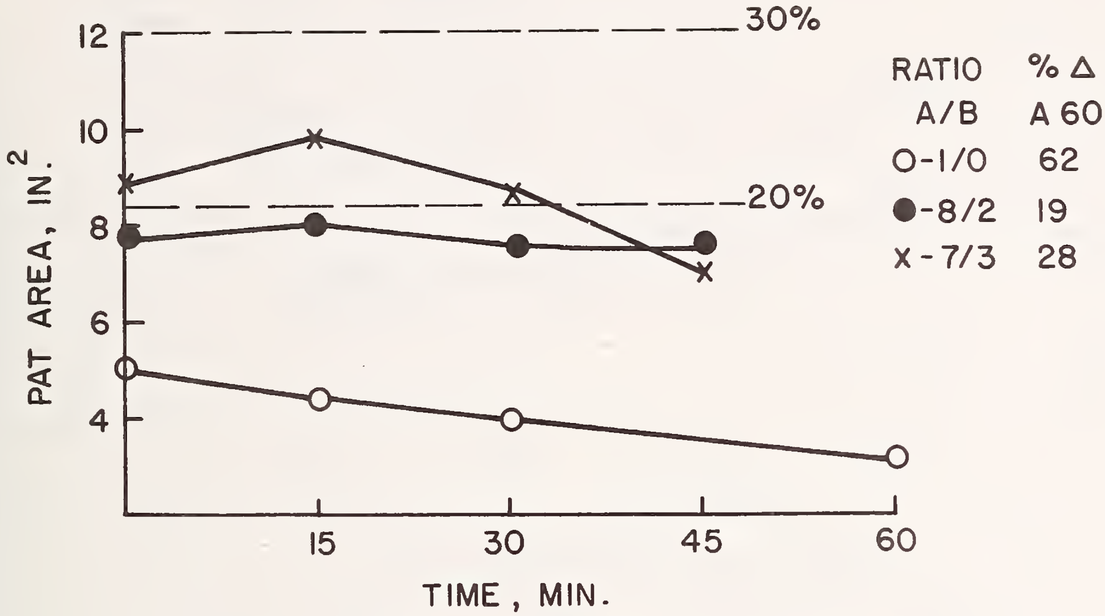

FIGURE 14A. CONSTANT DOSAGE 0.40% S/C

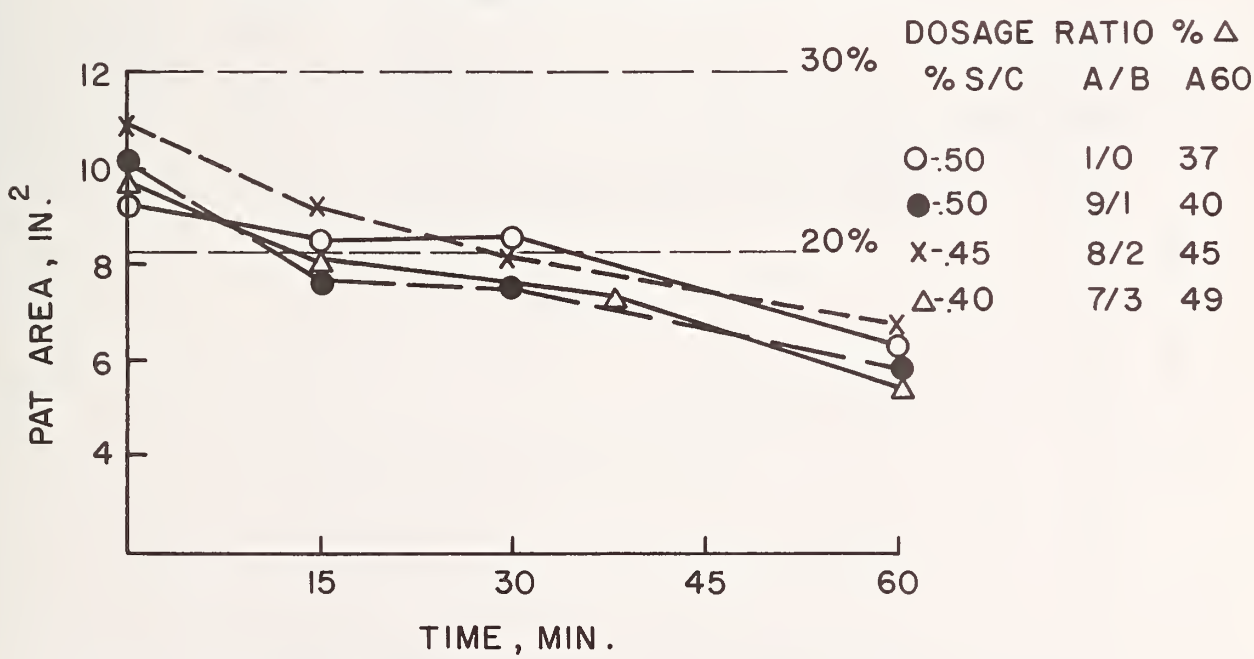

FIGURE 14B. CONSTANT INITIAL PAT AREA

FIGURE 14. PAT AREA VERSUS TIME FOR CEMENT NO.21731 WITH LOMAR D / PLASTIMENT COMBINATIONS

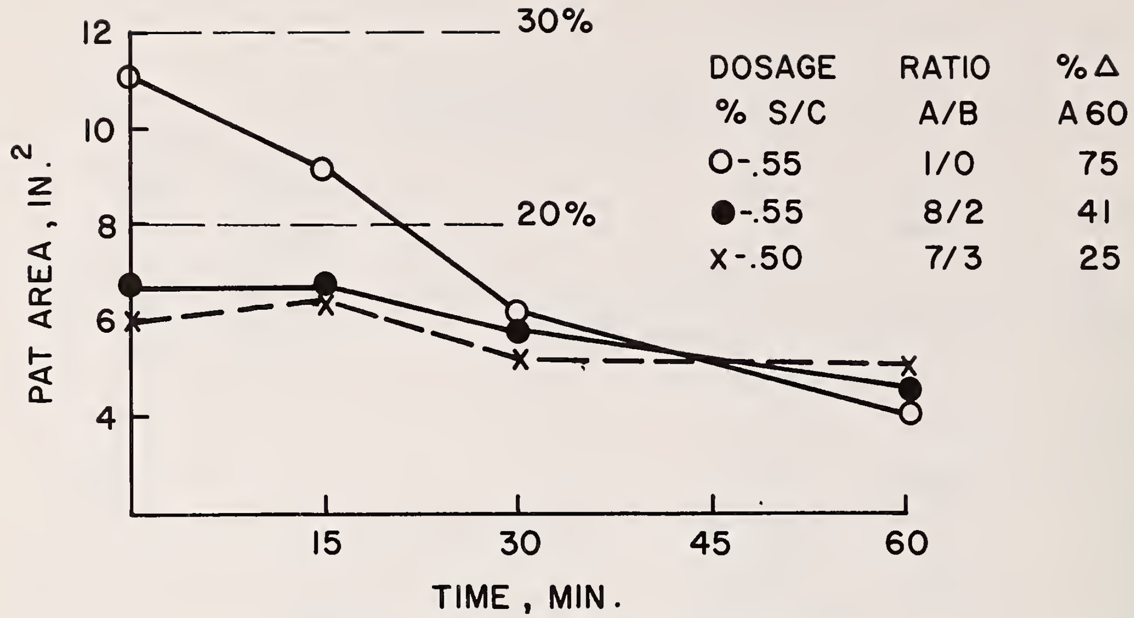

FIGURE 15A. CEMENT NO. 21731

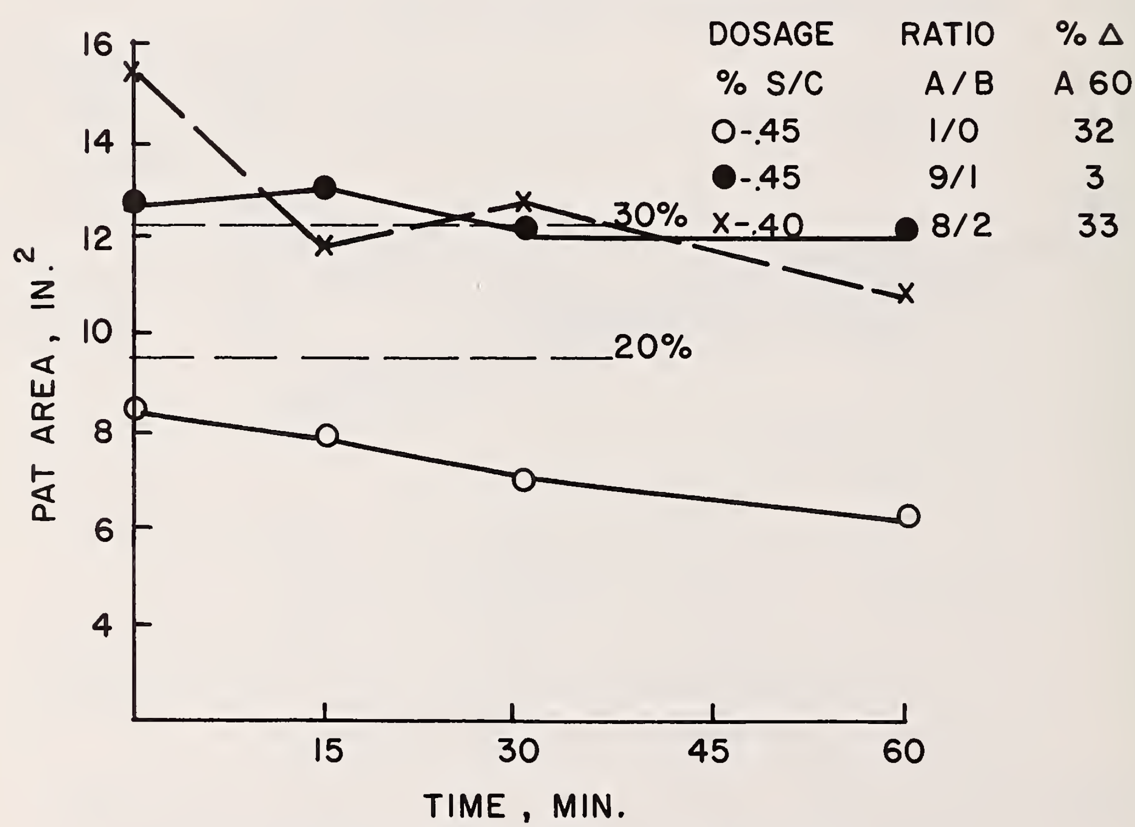

FIGURE 15B. CEMENT NO. LTS-25

FIGURE 15. PAT AREA VERSUS TIME FOR MELMENT L-10/ PLASTIMENT COMBINATIONS

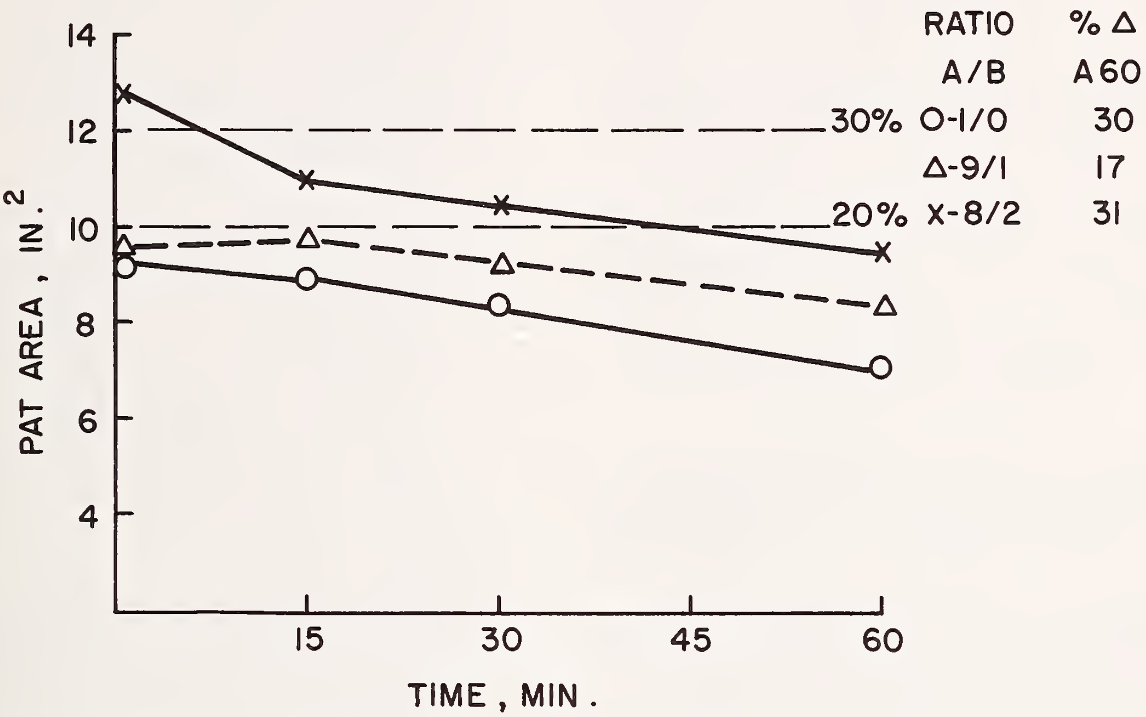

FIGURE 16. PAT AREA VERSUS TIME FOR CEMENT NO. LTS-25 WITH MIGHTY 150 / PLASTIMENT COMBINATIONS

although, here the differences are magnified (Figure 13). Delay in addition time while maintaining dosage of Lomar D constant results in very high initial pat area and a <u>negative</u> pat area loss! Reduction in dosage in order to maintain approximately equal initial pat area results in higher pat area loss rate for the delayed mix.

In summary, the use of delayed addition without a concomitant reduction in dosage will result both in higher initial pat area and reduced rate of pat area loss. If one takes advantage of the water-reducing properties of the delay and, therefore, reduces dosage so as to maintain equivalent pat areas, no reduction and possibly an increase in rate of pat area loss will be seen.

3.3.3 Effect of Binary Admixtures on Pat Area Loss

In section 3.2.3, the use of combinations of SWR and conventional water reducers (termed "binary" admixtures) was shown to be an effective means of reducing the amount of the more costly SWR and maintaining equal water reduction. The pat area loss characteristics of many of these combinations were examined. Figure 14A shows pat area loss plots of Lomar D/Plastiment combinations used with Cement 21731. Here the total amount of admixture was held constant at 0.40% s/c. Pat area loss was significantly less with this blend. When dosage was adjusted to achieve similar initial pat area, however (Figure 14B), pat area losses were <u>somewhat higher</u> in the blended admixtures.

Melment/Plastiment blends behaved in a similar manner (Figure 15A). Here the very high pat area losses encountered in the pure SWR paste were dramatically reduced through the use of a 7/3 binary ratio at slightly reduced dosage. When a low C_3A cement is used (Figure 15B), an optimum blend ratio of 9/1 is seen. At a lower ratio (8/2) pat area loss rises again to equal that of the unblended SWR. A similar optimum is seen in the case of a Mighty 150/Plastiment blend (Figure 16).

3.4 Summary

From consideration of all the data available from the mini-slump series, the following general conclusions can be drawn:

<u>Water Reduction Effects</u>

1. The required dosage (on a solids basis) to achieve equal water reductions is, in general, greater for melamine-based superplasticizers than for naphthalene-based ones.

2. The required dosage to achieve a given amount of water reduction is proportional to the C_3A content (determined via X-ray diffractometry) of the cement. At lower C_3A contents the total alkali content of the cement is of major importance in determining dosage requirement. Fineness of grind may also be an important variable.

3. When a superplasticizer is replaced with greater than 20% of a conventional water reducer based on sodium glucoheptonate, significantly less of the blend is needed to achieve equivalent water reduction. When calcium lignosulfonate is substituted for the glucoheptonate, an equivalent amount of the blend is needed to achieve the same water reduction. These effects are less pronounced with low C_3A cements.

4. When addition of the superplasticizer to the neat cement mix is delayed by approximately 5 minutes, the initial pat areas are dramatically increased. For many of the admixture/cement combinations studied, less than half as much admixture was required to yield pat areas equivalent to those obtained when the admixture was added initially to the mix water.

<u>Pat Area Loss Effects</u>

1. When cements having moderate to high C_3A contents are used, <u>all</u> of the superplasticizers studied showed increased pat area loss (as determined by qualitative assessment of the shape of the curve of pat area vs. time) over that of the control mixes, when added to the initial mix water.

2. For cements of low (<5%) C_3A content the overall rate of pat area loss when superplasticizers are employed is somewhat lower. When an under-sulfated, low C_3A cement was used, pat area loss was dramatically reduced. The use of low C_3A cement, however, is no guarantee that pat area loss will be reduced.

3. The effects of delayed addition on pat area loss are complex. The delay in addition will result in a higher initial pat area and a lower rate of pat area loss if dosage is maintained at a constant level. When dosage on delayed addition is adjusted (lowered) so as to obtain an initial pat area equal to the area for initial addition of admixture, the overall pat area loss may either increase or decrease depending upon the particular cement/SWR combination employed.

4. In some instances, use of a blend of superplasticizer and sodium glucoheptonate appears to reduce the rate of pat area loss. This is most pronounced for melamine-based blends when high C_3A cement is used.

4. Initial Slump Loss Testing in Concretes

At the conception of this program (1976), it was recognized that slump loss was one of the major obstacles which must be overcome if SWR are to achieve widespread usage in highway applications. A survey conducted early in the project indicated that many state highway agencies were having serious problems in placement of concretes containing SWR due to the high slump loss rates encountered. Most of the reported controlled studies at this point had been conducted by admixture manufacturers or allied interests. A symposium held in Ottawa, Canada, in May 1978, and later published by ACI (8) dealt heavily with the slump loss problem.

4.1 Materials

The objective of this phase of the program was to evaluate a number of the SWR in concrete mixtures of design similar to those typically used on highway construction. A target w/c ratio of 0.35 or lower was sought, as it is at these values of w/c ratio or below that strength, permeability, and durability properties should be dramatically improved. As the mini-slump series and chemical tests had shown, the admixtures fall into 3 major classes, one SWR typical of each class was chosen. Mighty-150 was chosen to represent the naphthalenes, Melment L-10 the melamines, and Alkanol the third class due to its difference in behavior with respect to dosage requirement and slump loss.

The concrete mixtures were chosen to represent two major classes of concrete used in highway applications. The first was termed a "pavement" mixture, typical of that used on full-depth paving jobs. The cement content was 564 lb/cu yd (335 kg/m^3), maximum aggregate size (crushed limestone) was 1.5 inches (38 mm), air content was held to 5 $\pm$ 1%, slump was adjusted to 2-3 inches (51-76 mm). The second class was termed "bridge deck" mixtures. For those the cement content was 658 lb/cu yd (390 kg/m^3), maximum aggregate size was 0.75 inches (19 mm), air content was held to 6 $\pm$ 1%, slump was adjusted to 2-3 inches. (51-76 mm).

Relevant aggregate properties and gradation data are shown in Table 10. The coarse aggregate was a crushed dolomitic limestone from Thornton, Illinois, having a high degree of angularity. The fine aggregate was a predominantly sub-angular natural sand from Elgin, Illinois, consisting of about 60% carbonate (dolomite) and 40% siliceous material.

Coarse aggregate was weighed air-dry, then soaked overnight prior to batching. Fine aggregate was used in a damp condition (moisture content somewhat above SSD).

Two cements were chosen for this phase of the slump loss testing. The first (No. 21795) was a high C_3A (8.4 potential, 4.1 XRD) high alkali Type I cement with relatively high Blaine fineness. The second (No. 21796) was a low C_3A (2.0 potential, 2.8 XRD) low alkali Type II cement with relatively low fineness. Complete chemical analyses for these cements can be found in Appendix D. Mini-slump testing indicated the following dosage requirements for Mighty-150 and Melment L-10 in pastes.

TABLE 9

Dosage Requirements in Cement Pastes

	20% Water Reduction	30% Water Reduction	
Cement	Mighty-150	Mighty-150	Melment L-10
21795	0.40	0.47	0.69
21796	0.16	0.31	0.42

The air-entraining agent used was neutralized vinsol resin (NVR) in 2% solution.

4.2 Control Mixtures

All concrete was mixed in a 0.75 cf (0.02m^3) counter-current, pan-type

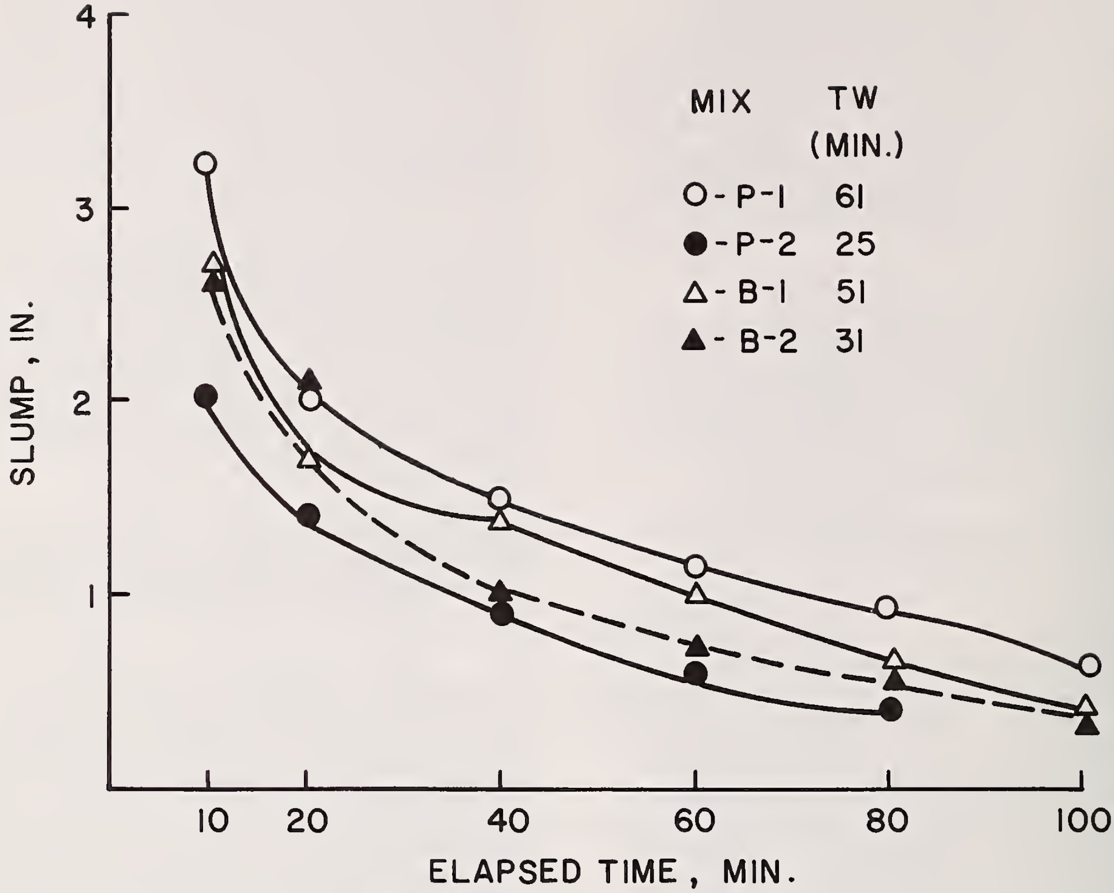

FIGURE 17A. SLUMP LOSS

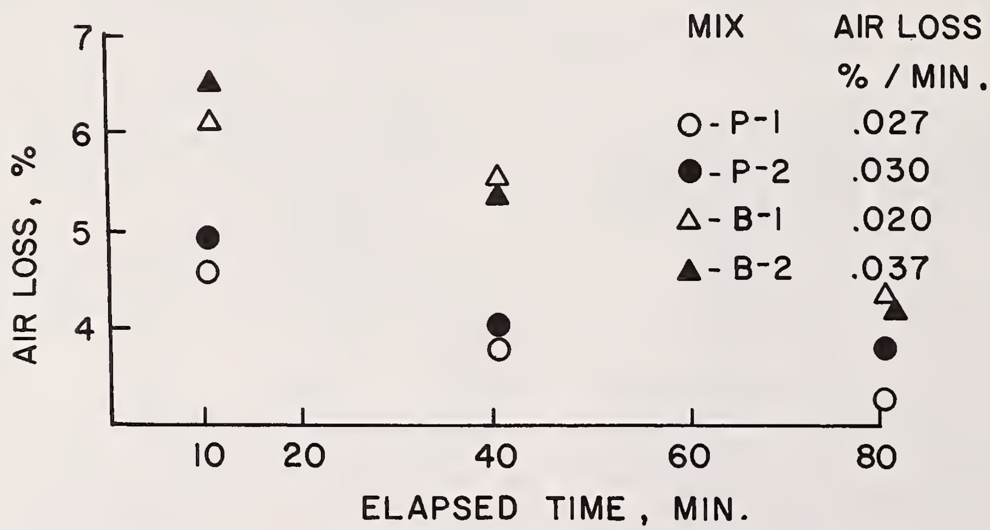

FIGURE 17B. AIR LOSS

FIGURE 17. SLUMP AND AIR LOSS IN CONTROL MIXTURES

TABLE 10

Aggregate Properties

Elgin, Illinois, Sand

Grading - % Retained on Sieve No. Indicated 4	8	16	30	50	100	F.M.	Bulk Specific Gravity, SSD	24-hour Absorption, % by Wt.
1	15	37	54	86	98	2.86	2.67	1.42

Thornton, Illinois, Crushed Limestone

Maximum Size of Aggregate, in.[1/]	Grading - % Retained on Sieve Size Indicated: 1.5 in.	0.75 in.	0.375 in.	No. 4	Bulk Specific Gravity, SSD	24-hour Absorption, % by Wt.
1.5	0	50	75	100	2.64	1.62
0.75	0	0	50	100	2.67	1.49

1/ To convert from in. to mm multiply by 25.4.

Lancaster mixer. Charging sequence was coarse aggregate, cement, sand. The mixer was then activated and the mix water containing the NVR was added within the first 20 seconds of mixing. The 3-3-2 mix cycle recommended in ASTM C192-76 was used in this phase of the program.

Concrete mix properties for control mixtures (no SWR) are shown in Table 11.

every 20 minutes and determining slump immediately after each remix. Air content was also measured at every other remix. Plots of slump versus time for the four control mixtures are shown in Figure 17A. The elapsed time is the time after initiation of the initial mix period. Thus, the first slump determination is made at an elapsed time of 10 minutes; (3-3-2), plus 2 minutes to set up and measure slump.

TABLE 11

Concrete Mix Properties

Control Mixtures

No.	Description	Quantities lb per cu yd[1/] - SSD: Water	Cement	Sand	Coarse Aggregate	% Sand Absolute Vol.
P-1	Paving Mix - Type I Cement	259	567	1,123	1,975	36
P-2	Paving Mix - Type II Cement	243	564	1,136	1,998	36
B-1	Bridge Deck Mix - Type I Cement	286	660	1,159	1,738	40
B-2	Bridge Deck Mix - Type II Cement	273	655	1,172	1,757	40

1/ To convert from lb per cu yd to kg/m^3 multiply by 0.594.

Relevant properties of the fresh concretes are given in Table 12.

4.2.1 Slump Loss - Control Mixes

The control mixtures were tested for slump loss by remixing for 2 minutes

The two parameters chosen to characterize slump loss are termed "slump window" (SW) and "total working time" (TW). The slump window is defined as the time interval (in minutes) during which the slump drops

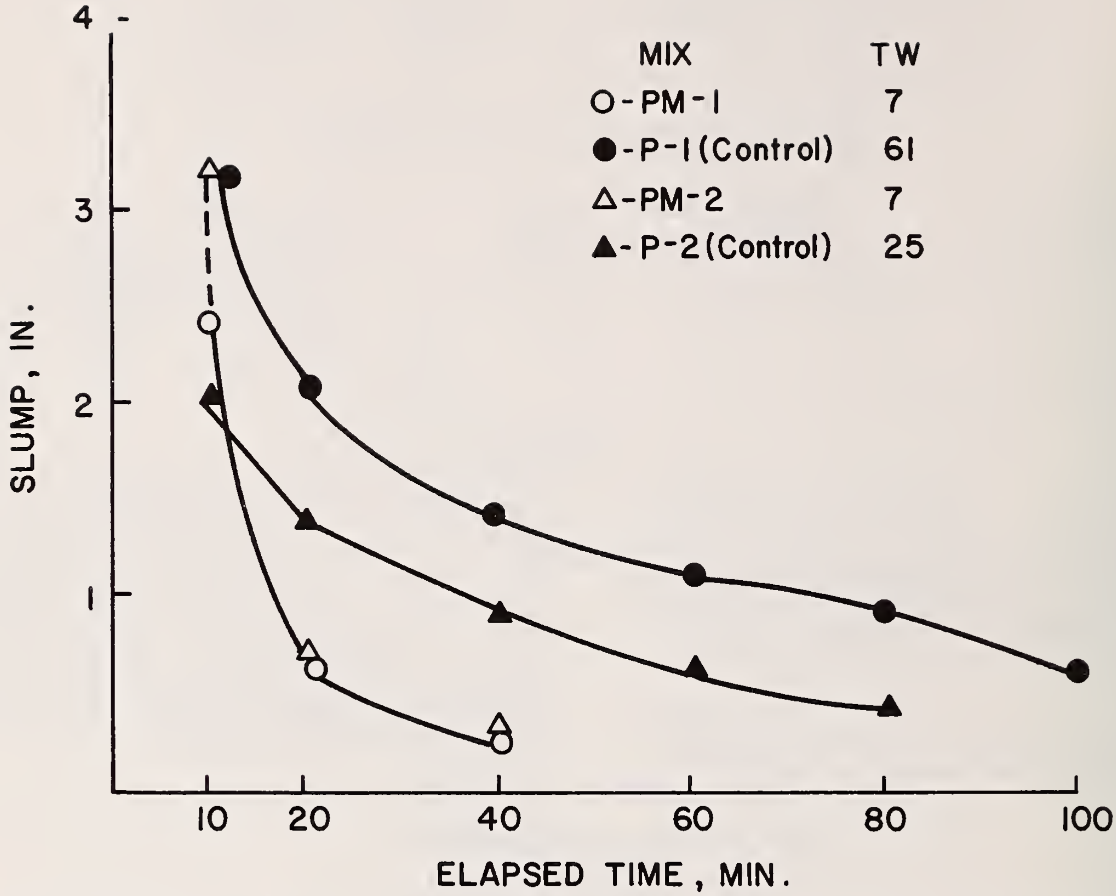

FIGURE 18. SLUMP LOSS IN PAVEMENT MIXTURES CONTAINING MIGHTY-150 AS COMPARED TO CONTROLS

TABLE 12

Properties of Fresh Concretes

Control Mixtures

No.	w/c	Slump in.	Content (%)	Unit Weight lb/cu ft 1/
P-1	0.46	3.2	4.5	145
P-2	0.43	2.0	4.9	146
B-1	0.43	2.7	6.1	142
B-2	0.42	2.6	6.5	143

1/ To convert from lb per cu ft to kg/m^3 multiply by 16.038.

from a value of 3.0 inches (76 mm) to 1.0 inches (25 mm). This represents the range of consistencies usually encountered in workable, highway concretes. The total working time is the time (in minutes) it takes the slump to drop from the initial value (which may be considerably greater than 3 inches (76 mm)) to a value of 1 inch (25 mm). For control concretes these two parameter will be essentially identical. For some of the later mixtures containing SWR, however, they may be significantly different when high-slump concretes are used.

The Type II cement appears to exhibit higher rates of slump loss than does the Type I. This was of considerable interest, as we could later examine the relative rates of slump loss when SWR were added to two cements having greatly different slump loss rates in admixture-free mixtures.

Plots of air loss vs time are shown in Figure 17B. The data at 80 minutes are open to question, as these represent mixtures having slump less than 1.0 inch (25 mm), where manual consolidation is a problem. If these points are ignored, the average rate of air loss in the controls is approximately 1 percent every 20 minutes.

4.3 Pavement Mixtures

4.3.1 Mighty-150 Initial Additions

Mixtures P-1 and P-2 were redesigned so as to obtain a net w/c ratio between 0.30 and 0.35. The cement contents were held constant, and the dosage of Mighty-150 adjusted so as to achieve a slump of 2-3 inches (51-76 mm). Mighty-150 was added to the mixer approximately 30 seconds after the start of mixing. After all the Mighty-150 was distributed evenly, the NVR was then added. This sequence will be termed "initial addition." It was found necessary to increase the sand content from 36 to 41% of total aggregate as the water-reduced mixture was somewhat harsh. The relevent data on the two mixtures containing Mighty-150 are shown in the following Table.

TABLE 13

Properties of Fresh Concrete

Mighty-150 Pavement Mixtures

No.	w/c	Slump (in.) 1/	Air (%)	Mighty-150 (% s/c)	Water Reduction %
PM-1	0.35	2.4	4.5	0.65	22.8
PM-2	0.33	3.2	5.5	0.76	23.5

1/ To convert from inches to mm multiply by 25.4.

It should be noted that the dosages of Mighty-150 necessary to achieve water reductions of 23% in these concretes were much greater than the doses necessary to achieve 30% water reduction in the neat pastes (see Table 10). This corroborates earlier work (9) which showed the effectiveness of water-reduction to increase with increasing cement content. The neat paste system can be taken as the extreme case (100% cement content) and, therefore, affords the maximum possible water reduction. Additionally, the Type II cement required a higher dosage of Mighty-150 to achieve a given water reduction then the Type I cement in concrete, while in paste the opposite was true. This can most likely be explained by the use of a slump range in the concrete mixtures, as is common practice. For this reason the Type I cement required less admixture as the slump achieved was lower. Preparation of the concrete mixtures at exactly equal slump would have been extremely wasteful in time and material. As it was, for some of the batches 6 or 7 trial mixtures were necessary before the specified slump and air contents were achieved. It is, therefore, not surprising that field experiences with SWR have exhibited many problems in control.

Plots of slump loss for these mixtures are shown in Fig. 18, with controls included for comparison. Rates of slump loss are extremely high, concretes becoming essentially unworkable within

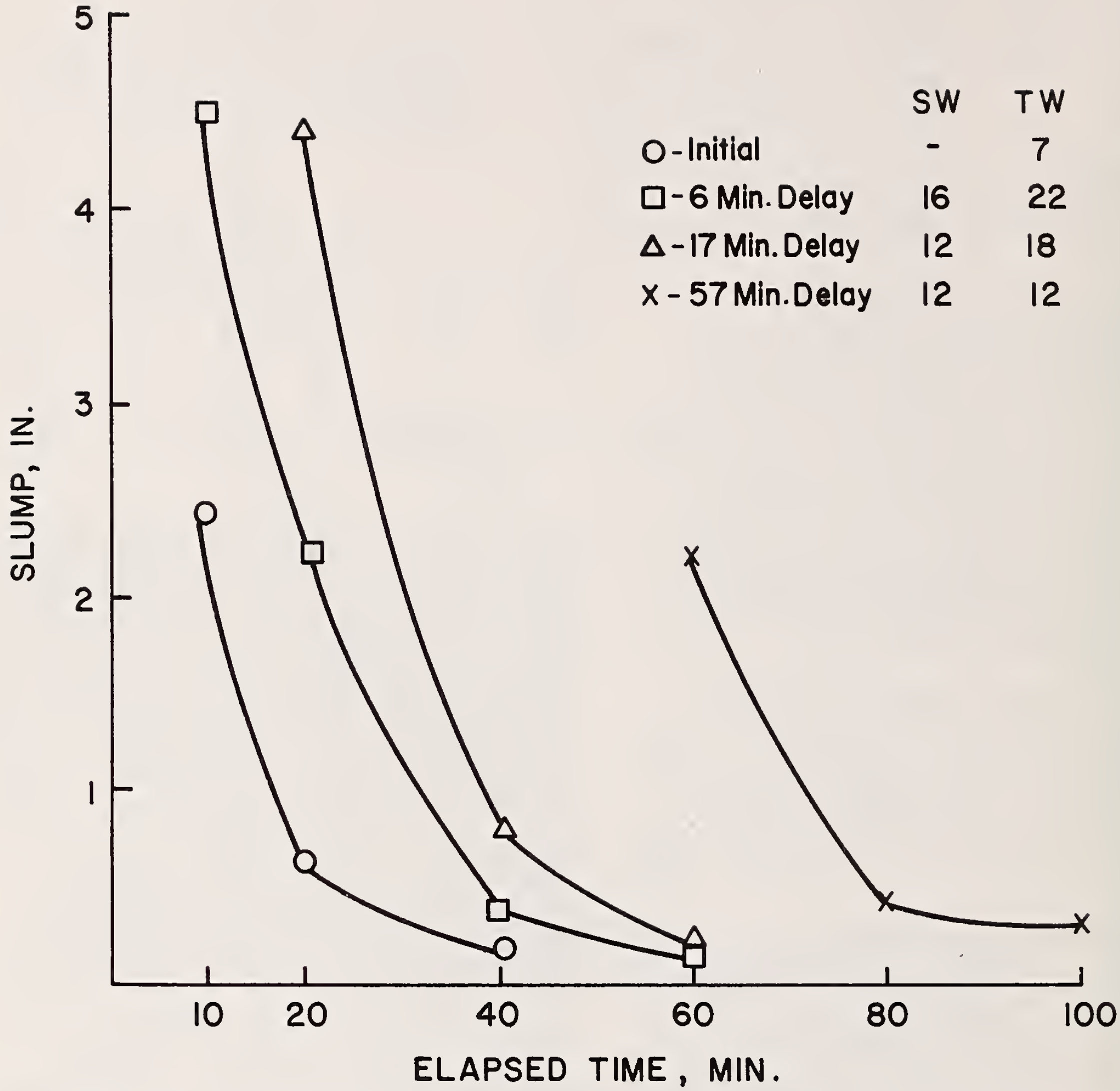

FIGURE 19. EFFECT OF DELAYED ADDITION ON SLUMP LOSS. TYPE I CEMENT WITH MIGHTY-150

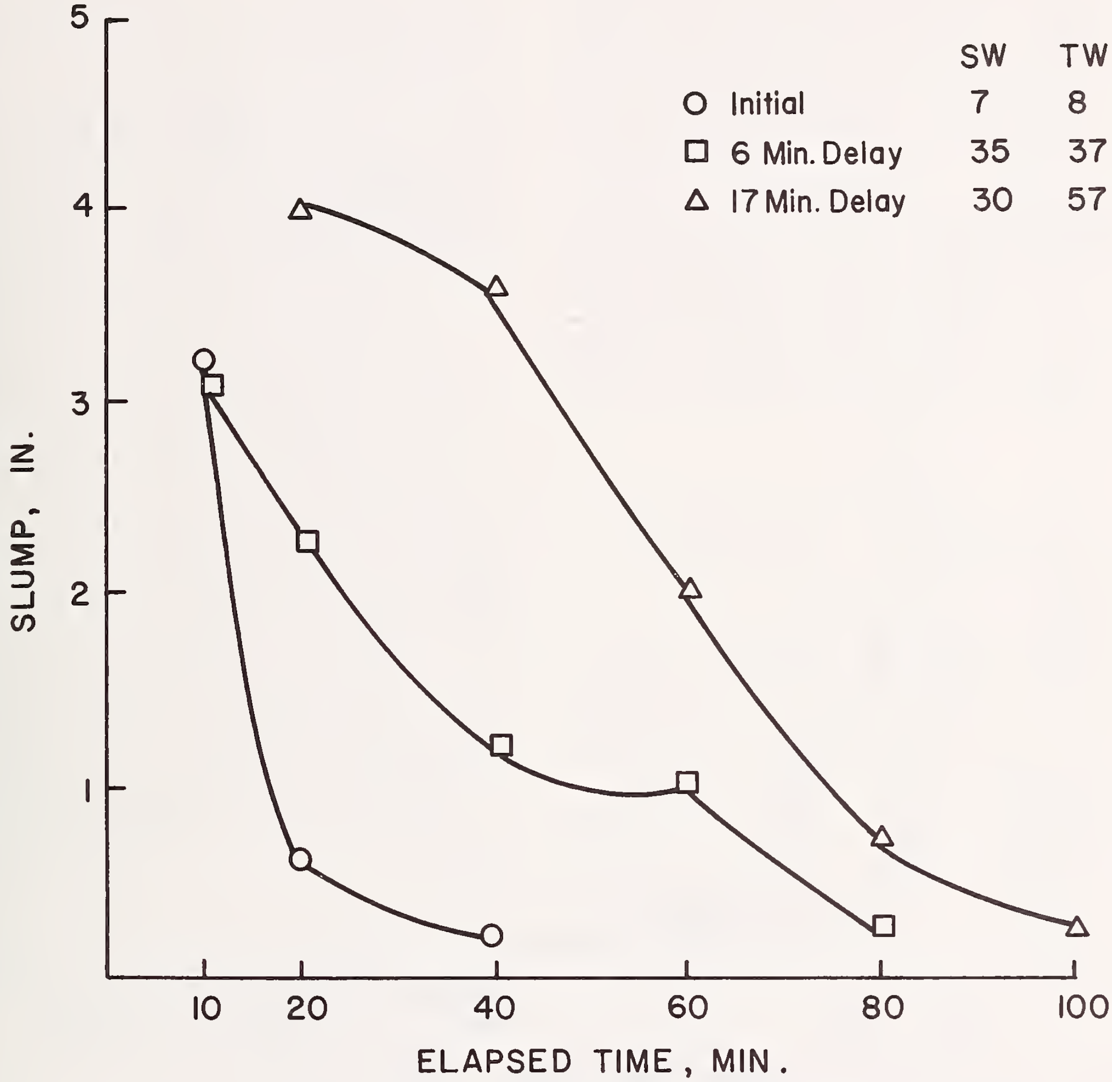

FIGURE 20. EFFECT OF DELAYED ADDITION ON SLUMP LOSS.
TYPE II CEMENT WITH MIGHTY-150

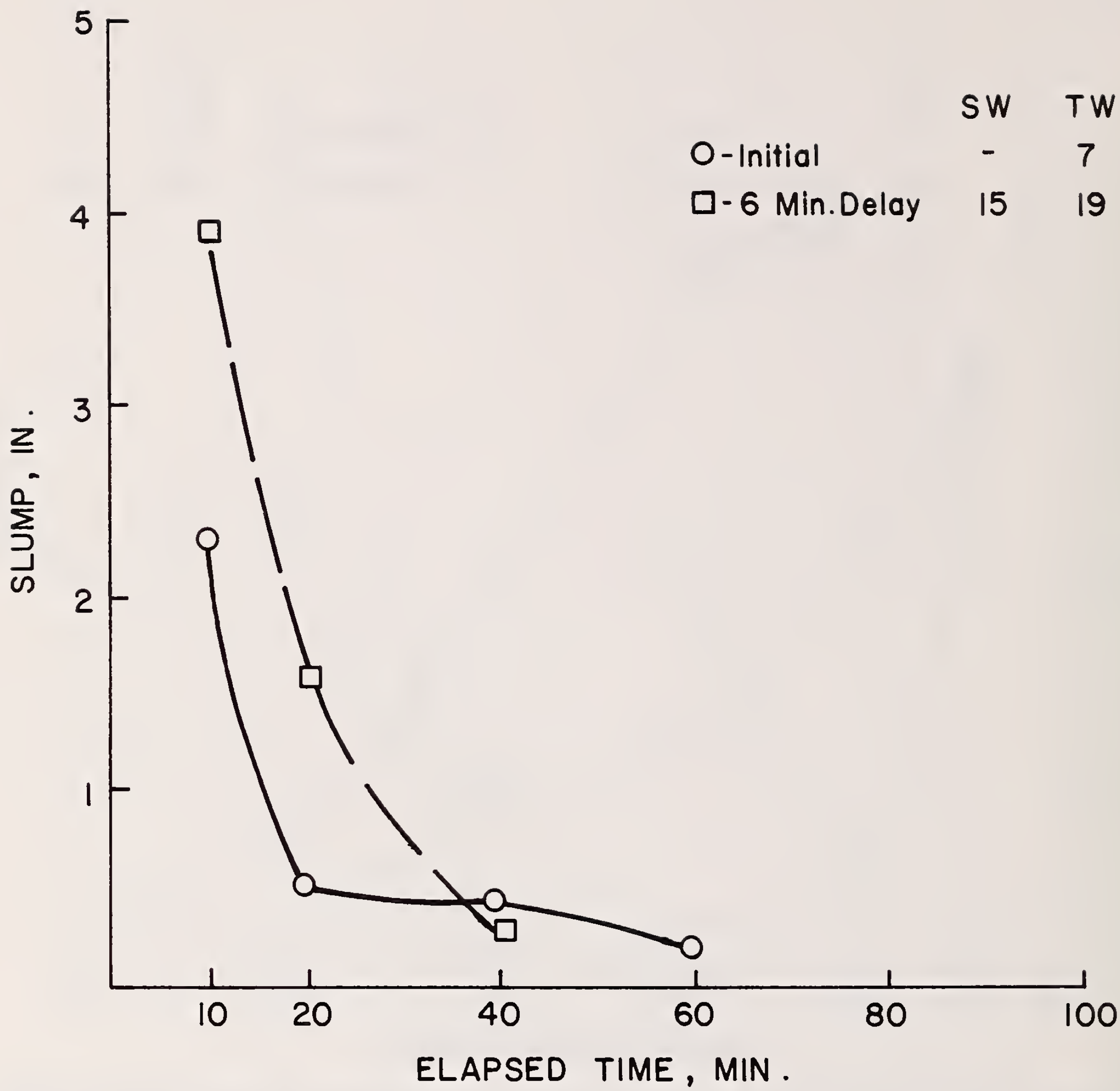

FIGURE 21. SLUMP LOSS IN NON-AGITATED MIXTURES

10 minutes of discharge. Curves for Type I and Type II cement concretes are nearly identical, showing slump loss in the water-reduced mixtures containing Mighty-150 to be independent of the rate of slump loss in the controls.

Delayed Additions

The mini-slump testing indicated that some benefits might be derived by delay in addition of SWR. In order to investigate this in concrete, mixtures were prepared where the admixture was added at the beginning of the second mix cycle (6-minute delay), at the beginning of the first remix (17-minute delay), and at the beginning of the third remix (57-minute delay). Figure 19 shows the gains in working times which can be achieved using this approach for the Type I concretes. The results are even more apparent for the Type II concretes (Figure 20). Here the delays in addition allow a return in working times to a level greater than the control. The 17-minute delay might be useful as a jobsite addition, if a means were available for remixing on-site. Unfortunately, most contemporary paving projects utilize central mixing, and the concrete is delivered to the site in non-agitating "dumpcrete bodies." Thus, the admixture would need to be added at the plant, and a total working time of 37 minutes (assuming a 6-minute delay could be used at the plant) might be insufficient if long haul times or traffic delays were encountered. It is doubtful whether the 17-minute delay would be a practical solution to the problem, as this would result in long holding times and reduced production rates.

In the case of pavement operations, as mentioned above, there is usually no opportunity for remixing of the concrete during or after transport to the jobsite. In order to see what effect this would have on slump loss, two mixtures were prepared using Mighty-150 and Type I cement similar to Mixture PM-1 (Table 13). In these mixtures, however, no remixing was done after the end of the last mix cycle. Slump was taken at 20 minute intervals. Results are shown in Figure 21. Comparison with the remixed batches (Figure 19) shows little difference in slump loss characteristics between the two cases.

Repeated Dosing

Repeated doses of SWR have been used to maintain workability of both water-reduced and flowing concretes. A process utilizing redosing with 0.1% Mighty-150 at 15 minute intervals (10) was used to maintain slump levels at 4-6 inches (100-150 mm) for periods up to 90 minutes after initial dosing. Seabrook and Malhotra (11) used repeated doses equal to the original dose of 3 different SWR in order to maintain concrete in a "flowing" condition. The technique utilized in the first approach (i.e., adding small amounts of SWR in order to maintain slump at conventional levels) did not negatively affect the strength development of the concrete, while more than 2 redoses using amounts equal to the original dose did in fact result in strength reductions in some cases. Although these techniques would prove difficult in practice and present additional control problems, a limited amount of work on this aspect was attempted. Mixtures were prepared using initial addition of Mighty-150. The slump loss cycle was then run as before, with the exception that additional Mighty-150 was added at the beginning of each 2 minute remix. Results for Type I and Type II cement concretes are shown below.

TABLE 14

Use of Redosing to Maintain Slump

	Type I		Type II	
Time	Dose (% s/c)	Slump (in.)1/	Dose (% s/c)	Slump (in.)
Initial	0.65	2.1	0.72	2.6
20 min.	0.16	2.7	-	0.8
40 min.	0.08	1.7	0.15	1.5
60 min.	0.11	1.9	0.17	1.3
80 min.	0.11	1.5	0.17	1.3
100 min.	0.11	1.2	0.17	1.4
120 min.	0.15	2.3	0.23	1.3
Total	1.37		1.61	

1/ To convert from in. to mm multiply by 25.4.

By addition of from 0.1% to 0.2% (s/c) of Mighty-150 every 20 minutes it was possible to maintain the slump within the range of 1-2 inches. After 2 hours of testing the total amount of Mighty-150 added was approximately equal to a single redose. In practice, it is likely that some type of automatic dispensing equipment tied to an automatic slump meter (such as a "Tele-A-Slump"1/ or similar device) would be needed to ensure adequate control in field situations.

Use of Binary Admixtures

Results of "mini-slump" testing (see Section 3.3.3) indicated that a blend of super water-reducer and conventional

1/ Concrete Controls Co., Wheaton, IL.

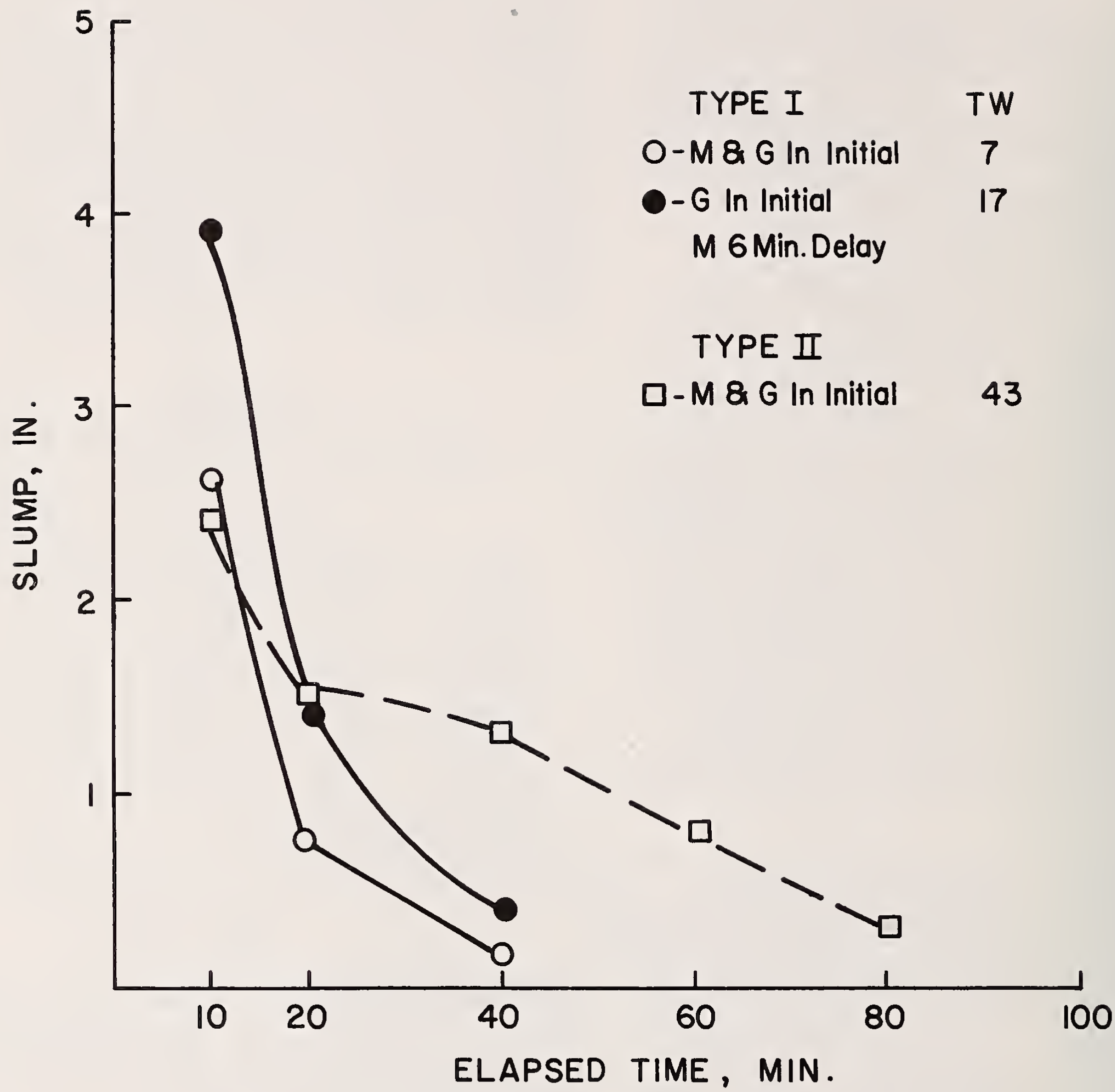

FIGURE 22. EFFECT OF BINARY ADMIXTURES ON SLUMP LOSS

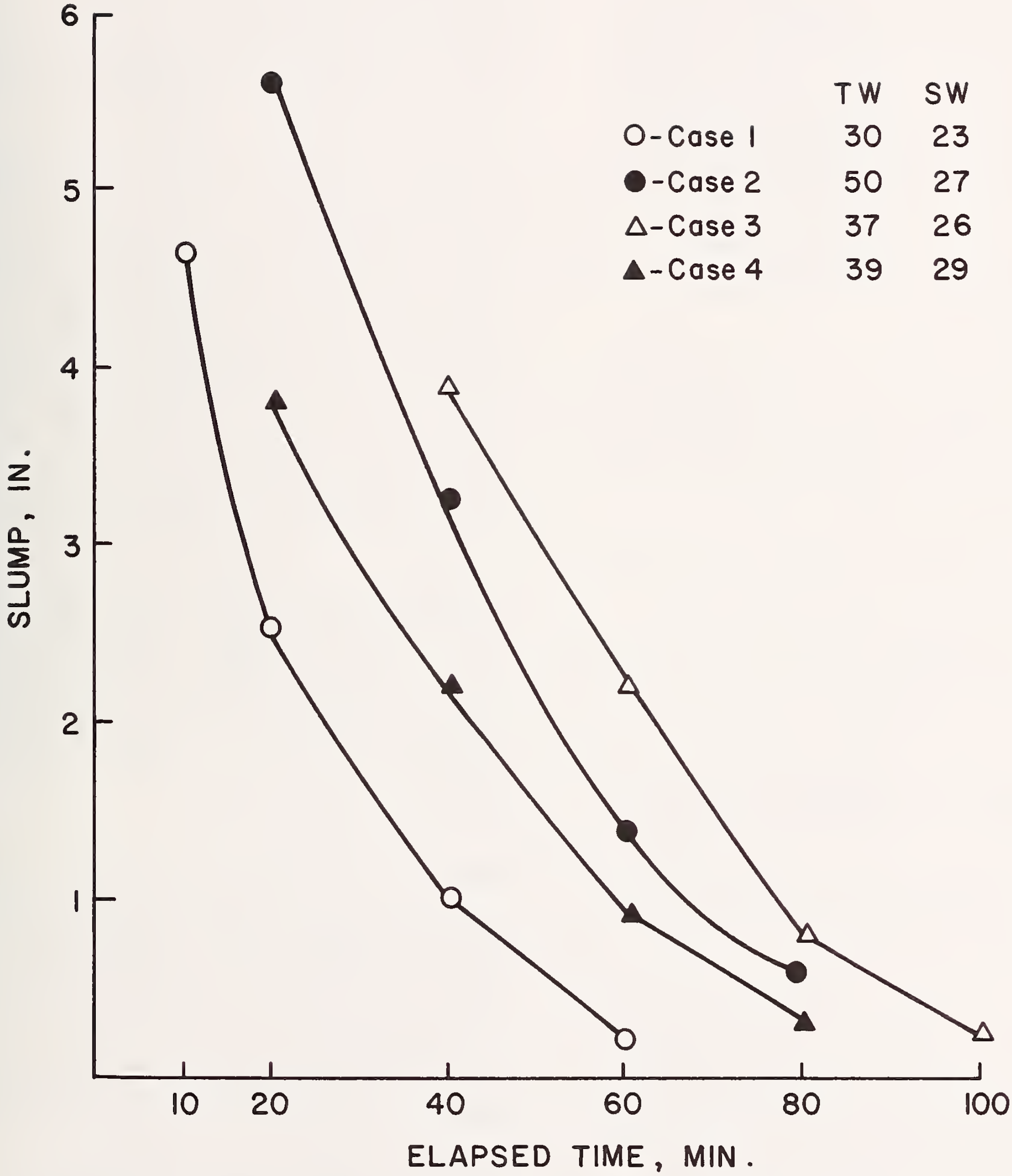

FIGURE 23. EFFECT OF ADDITION SEQUENCE OF BINARY ADMIXTURES ON SLUMP LOSS

glucoheptonate-based water-reducer might help to increase efficiency and reduce rates of slump loss. A mixture consisting of 85 parts by weight of Mighty-150 and 15 parts by weight of sodium glucoheptonate[1/] was prepared and added to selected mixtures in amounts equal to the total amount of Mighty-150 used in previous tests. This corresponds to dosages (by weight of cement) of 0.56% Mighty-150 and 0.10% of sodium glucoheptonate. In previous mixtures using straight Mighty-150 a dosage of 0.65% was used. The components were added both as a blend in the first mix cycle, and separately by adding the glucoheptonate (G) in the first mix cycle, and the Mighty-150 (M) in the second mix cycle. Results are presented in Figure 22 for Type I and II cements. For Type I cement results are almost identical to the cases where Mighty-150 alone was used. For Type II cement, however, total working time was increased from 7 minutes to 43 minutes, without the use of any delay in addition.

Further tests were designed to investigate the effects of split additions of a mixture of Mighty-150 and sodium glucoheptonate. Proportion of M-150 to sodium glucoheptonate was 85/15 by weight of solids. Results are presented in Figure 23 for 4 cases:

1. Blend added during the second mix of the 3-3-2 cycle.

2. Glucoheptonate added during the second mix of the 3-3-2 cycle, then Mighty-150 added during the first remix (10 minute later).

3. Glucoheptonate added during the second mix of the 3-3-2 cycle, then M-150 added during the second remix (20 minutes later).

4. Blend added during the first remix (10 minutes after the 3-3-2 cycle).

Results (Figure 23) show that the highest initial slump and longest working times were achieved in Case 2, when the glucoheptonate was added in the second mix cycle and the Mighty-150 added during the first remix. In this case the total working time (TW) after addition of Mighty-150 was 50 minutes, which should be sufficient for most applications. A delay of only 10 minutes more in addition of Mighty-150 (Case 3), however, drops the working time to 37 minutes. The slump windows (SW) are roughly similar, thus the times during which these concretes would have the consistency of normal highway concretes are about the same, and are only slightly better than those achieved simply by delay in addition of Mighty-150 alone (see Figure 19).

An examination of the concrete cast from mixtures where the blend of Mighty-150 and glucoheptonate had been added in the delayed addition mode indicated retardation had taken place. The Type I cement concrete had set, but was still "green", and exhibited little strength, a 3-inch (76 mm) prism broke in two upon stripping out of its mold the following day. The Type II cement concrete had not reached final set after an overnight cure.

Some work was also done with a commercial retarding version of Mighty-150 (RD2). When this was added at a dose equal to that of Mighty-150 (0.65% s/c) at the second mix cycle, slump loss similar to Case 1 in Figure 23 was seen. Examination of cast concrete the following day showed that severe retardation had occurred in this mixture. That is, the performance of the commercial product was very similar to that of the laboratory blend. The dosage of RD2 was then decreased to 0.34% s/c. This reduced the initial slump to 2.3 in. (58 mm). Slump loss, however, was very rapid, dropping to 0.4 in. (10 mm) within 10 minutes.

In summary, the use of a blend of SWR and commercial water-reducer does allow significant reduction in rate of slump loss, especially when used in the delayed addition mode. Severe retardation effects and the difficulty of closely timing additions, however, make this an impractical solution to the slump loss problem.

Use of Short Mix Cycles

Conversations with local concrete suppliers utilizing central mixing operations indicated that use of delayed addition of admixtures would seriously affect the economics of production. Their feeling was that any mix cycle lasting longer than 90 seconds would not be acceptable. If SWR were to be used in central mix operations techniques would need to be developed which would allow their utilization in a short mix cycle.

A series of mixtures employing a 90 second mix in a counter-current pan mixer was prepared in an attempt to simulate central mix operations. Mighty-150 was used at dosages (solids by weight of cement) of 0.78, 0.98, and 1.26 percent. The previously described "pavement mixture" was used. Mighty-150 was added in the mix water, and at delay times of

1/ Seqlene ES-50 (Pfanstiehl Laboratories Waukegan, IL).

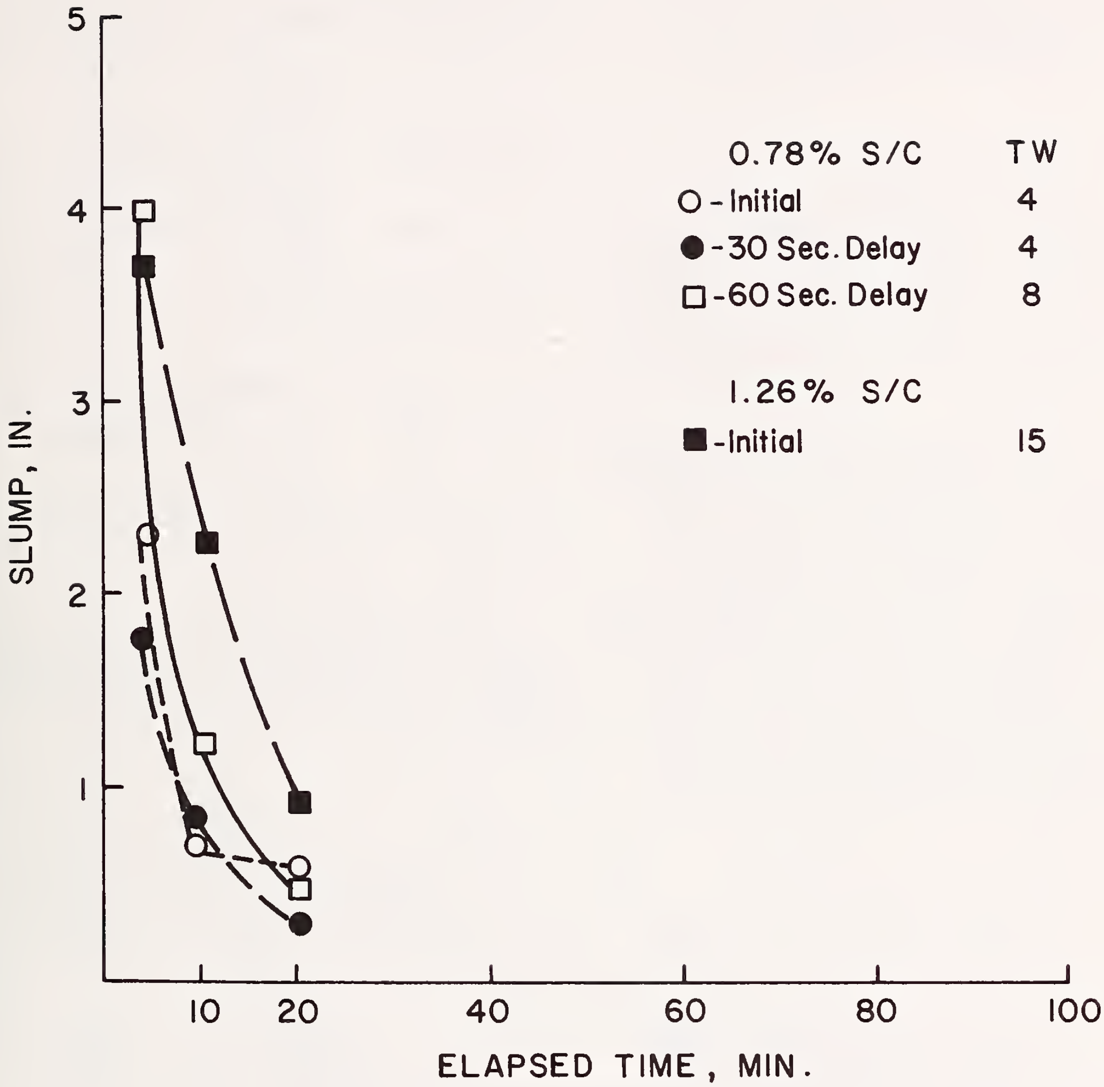

FIGURE 24. SLUMP LOSS IN MIXTURES USING SHORT MIX CYCLE

30 seconds and 60 seconds. Results are presented in Figure 24. Working time was increased slighty by a 60 second delay in addition. Even at a very high dose of Mighty-150, however, total working time was relatively short. It should be noted that slump loss was greater for these mixtures than for those employing the 3-3-2 cycle, indicating the difficulties associated with use of super water-reducers in operations where a delay or rest period cannot be economically justified.

Air Loss in Fresh Concretes

During the course of the slump loss investigations a number of mixtures were also tested for loss of air with time. The possibility of a more rapid rate of air loss in concretes containing SWR may help to explain the decreased durability which some have seen in concretes utilizing these admixtures.

Air contents were determined immediately after the initial slump test in mixtures containing SWR, and again at the second remix. Using this procedure only two reliable measurements were obtained in most instances, as the high rates of slump loss meant that in most cases slump had dropped below 1.0 inches (25 mm) by the third remix, making it difficult to accurately determine air content. The rate of air loss is, therefore, expressed as a difference between the readings obtained after the initial mix and the readings obtained at the second remix:

$$\text{Air Loss Rate (\%)} = \frac{A_i - A_r}{\Delta t} \qquad (1)$$

where: A_i = initial air content (% by volume)

A_r = air content measured after second remix (% by volume)

Δ_t = elapsed time between remixes (usually 30 minutes)

Data are presented in Table 15 for controls and Mighty-150 mixtures prepared using Type I and Type II cements. Initial air contents for these mixtures ranged between 4.5 and 5.5 percent, with the exception of the 17 minute delay mix with Type II cement which had a higher initial air content of 6.9 percent.

In all cases the rates of air loss in mixtures containing the SWR are greater than in the controls. Although slump values on some of the delay mixtures were greater than those of the corresponding control, which might account for the more rapid air losses, many of the mixtures having initial slumps in the same range

TABLE 15

Rate of Air Loss in Concretes

Containing Mighty-150

Addition Time of Mighty-150	Remixing	Rate of Air Loss % Type I	Rate of Air Loss % Type II
Control	Every 20 min.	0.027	0.030
Initial Mix	Every 20 min.	0.070	0.117
6 min. Delay	Every 20 min.	0.070	0.057
17 min. Delay	Every 20 min.	-	0.090
Initial Mix	None	0.043	-
6 min. Delay	None	0.087	-

as the controls *also* showed high air loss rates.

4.3.2 Melment Mixtures

Melment L-10 SWR was used in mixtures having the "pavement" mixture design. Batch characteristics are given in Table 16.

TABLE 16

Properties of Fresh Concrete

Melment L-10 Pavement Mixtures

No.	w/c	Slump 1/ (in.)	Air (%)	Melment L-10 (% s/c)	Water Reduction (%)
PL-1	0.35	2.4	5.4	0.92	23.2
PL-2	0.33	2.2	5.0	0.99	22.2

1/ To convert from in. to mm multiply by 25.4.

Dosages of Melment L-10 are higher than those for Mighty-150 in comparable mixtures.

This substantiates the mini-slump results on the same two cements (see Table 10). Mixtures were prepared utilizing addition of Melment in the initial mix period ("initial" addition), as well as in the second mix cycle (6 min. delay). Plots of slump versus time are shown in

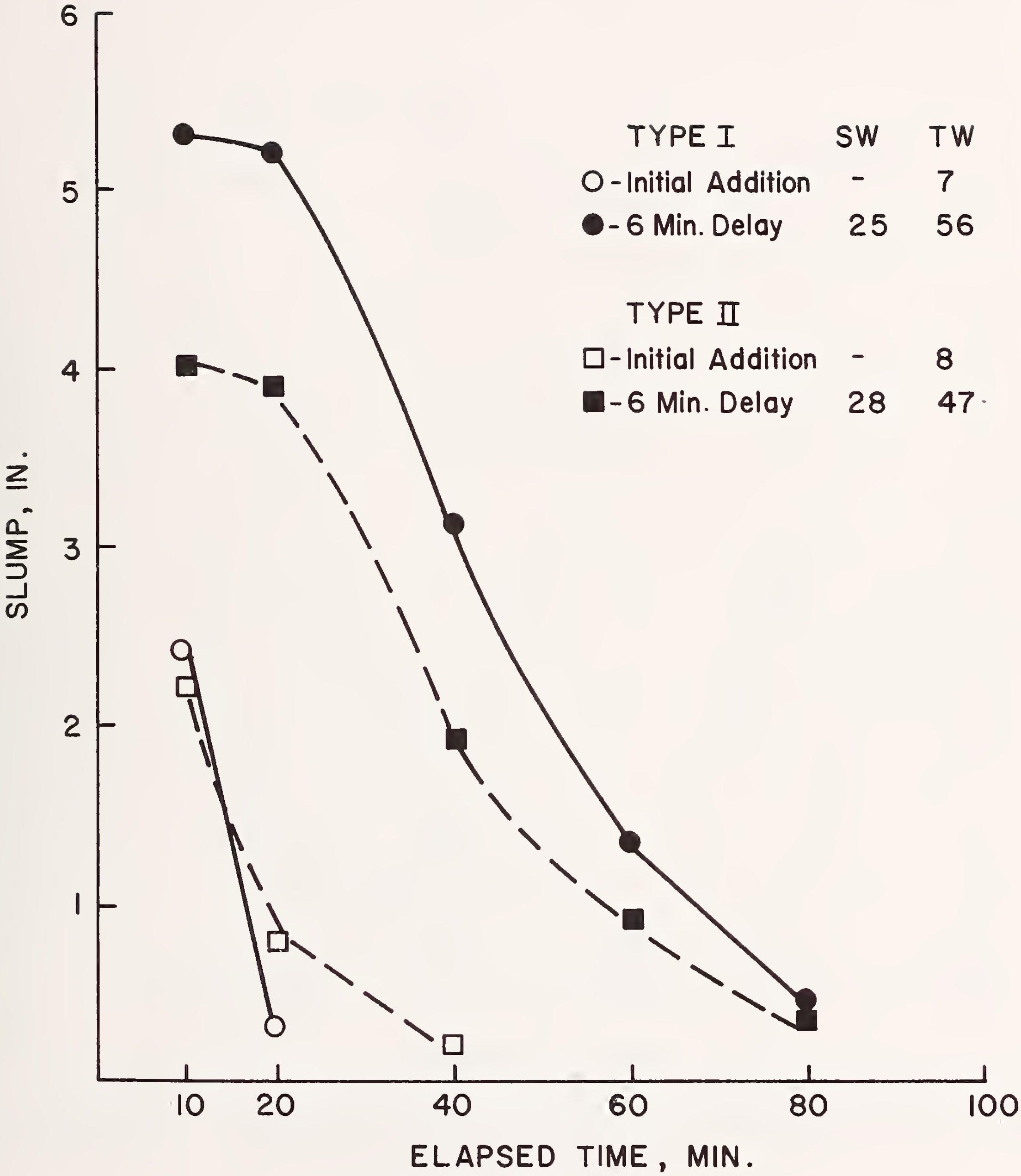

FIGURE 25. SLUMP LOSS IN PAVEMENT MIXTURES WITH MELMENT L-10

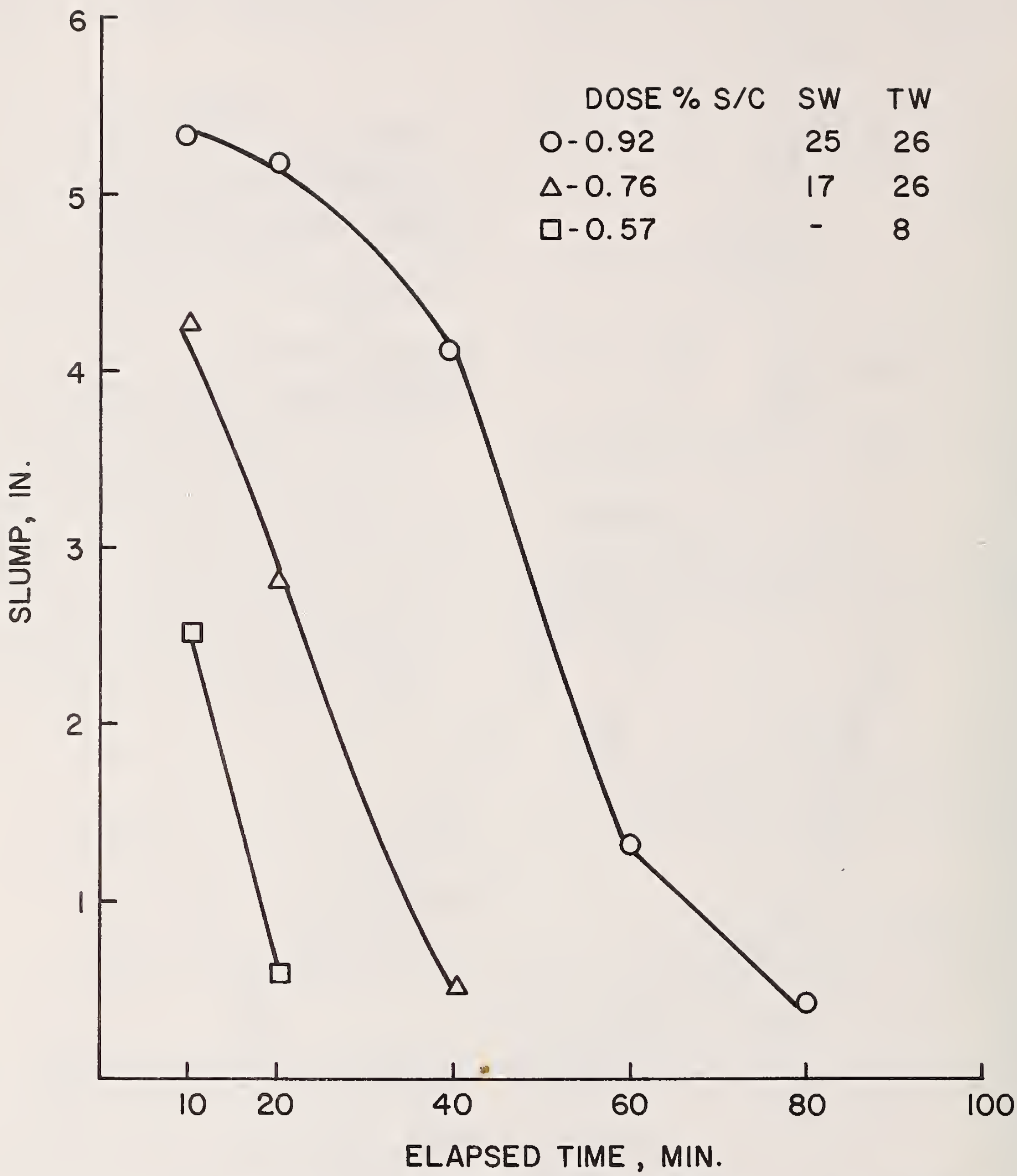

FIGURE 26. EFFECT OF DELAYED ADDITION ON SLUMP LOSS IN PAVEMENT MIXTURES WITH MELMENT L-10

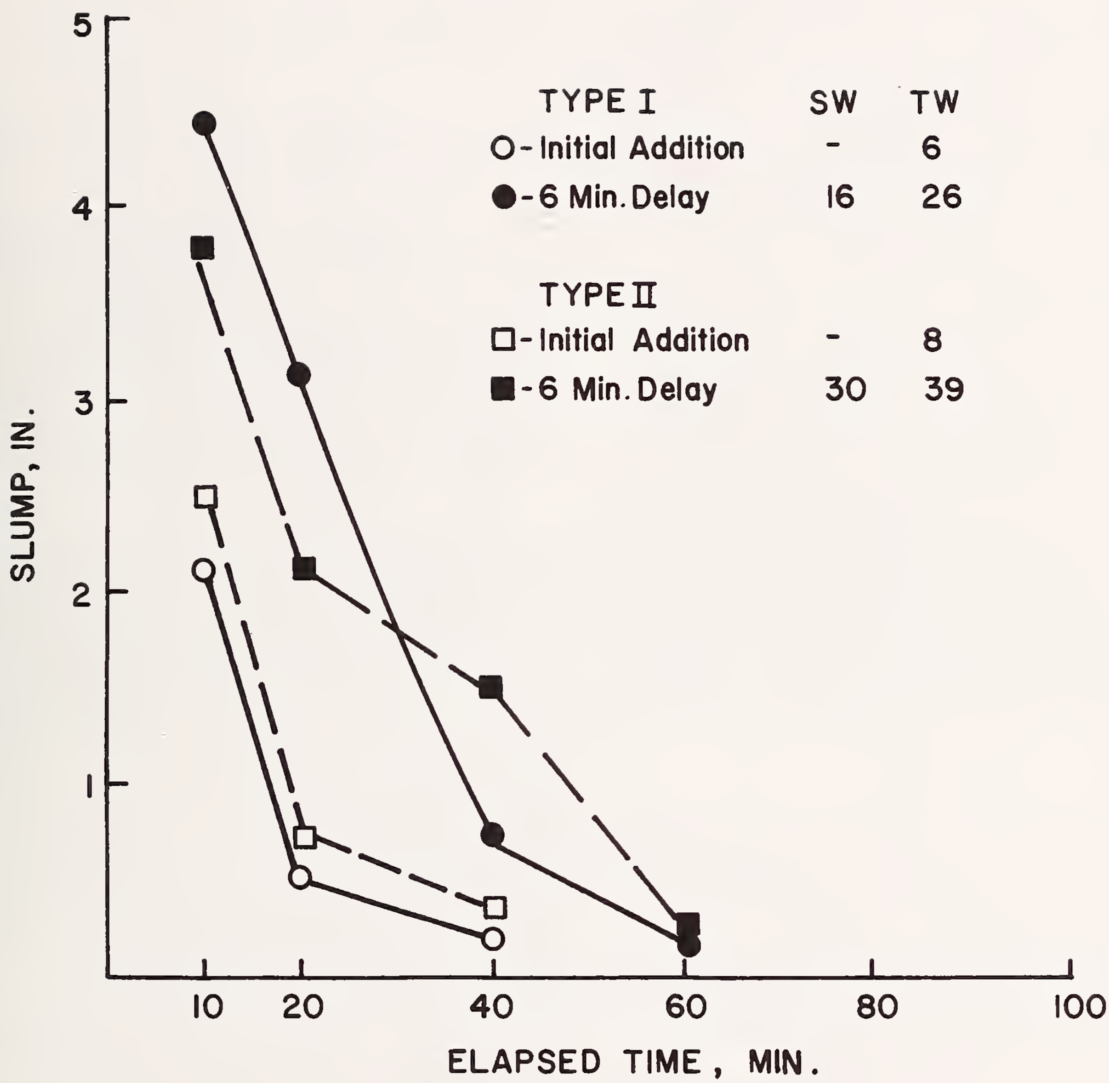

FIGURE 27. SLUMP LOSS IN BRIDGE DECK MIXTURES WITH MIGHTY-150

Figure 25. The addition of Melment L-10 in the initial mix period produces the typical high rate of slump loss seen with the Mighty-150 when added in the same manner. The 6 min. delay affords a significant increase in available working times, both for Type I and Type II cements. A comparison of these plots with those for Mighty-150 (Figures 19 and 20) indicates that slump loss behavior for the initial addition mode is virtually identical for the two admixtures. In the case of delayed addition Melment L-10 offers greater working times for the Type I cement, working times for the Type II cement are similar (though not identical) for the two SWR. Recognizing the large differences in slump loss behavior noted for the various cement/admixture combinations screened in the "mini-slump" series, one would be ill advised to generalize these results as typical of all Type I and Type II cements currently available.

The delayed addition mode results in an increase in slump as well as an increase in working time. A few tests were conducted to see what the effect of reducing the dosage (and hence reducing initial slump) in the delayed mode would have on the rate of slump loss. The percentage of Melment L-10 was decreased while holding the water-cement ratio constant. Results are shown in Figure 26. One can see that slump loss increases with a decrease in initial slump brought about by the reduction in admixture concentration. Thus, it appears that no reduction in admixture dosage can be made without sacrifice of workability with time.

4.4 Bridge Deck Mixtures

Concrete mixtures were prepared utilizing a design typical of that used in full depth bridge deck casting (see Table 11 for mix proportions). Mighty-150 was added so as to reduce the water-cement ratio below 0.35 and obtain water reduction between 20-25 percent. Properties of the fresh concretes containing the Mighty-150 are shown in Table 17.

A comparison with the water-reduced pavement mixtures shows that at comparable water-cement ratio and water reductions, significantly less Mighty-150 is required in the "bridge deck" mixtures. This can be attributed to the higher paste content in these mixtures, which increases the effectiveness of the SWR. It is also of interest to note that the amounts of Mighty-150 needed to achieve approximately 20% water reduction in these relatively rich mixtures are still far above the amounts needed in the neat pastes (Table 10).

TABLE 17

Properties of Fresh Concrete

Mighty-150 Bridge Deck Mixtures

No.	w/c	Slump (in.)1/	Air (%)	Mighty-150 (% s/c)	Water Reduction (%)
BM-1	0.34	2.2	5.1	0.58	21.6
BM-2	0.32	2.6	6.3	0.54	22.0

1/ To convert from in. to mm multiply by 25.4.

Slump of these mixtures versus time is shown in Figure 27. Slump loss characteristics for initial additions are almost identical to the pavement mixtures (see Figures 19 and 20), that is, extremely high rates of slump loss are evidenced. For the case of a 6 min. delay in addition of the SWR, the working times for the bridge deck mixtures are also very similar to those of the pavement mixtures.

As with the pavement operation typical mix procedures in use in the ready mix industry do not allow for a delay similar to that used in the ASTM laboratory mix cycle. Generally, the materials are batched and mixed in the ready-mix truck for a period of about 5 minutes prior to transportation to the job site. A few tests were done using a 5 minute continuous mix, with the addition time of Mighty-150 being varied at 1 minute intervals during this mixing period. Immediately after the 5 minute period slump and air contents were determined and the slump loss cycle was initiated. Results are shown in Figure 28. Longest working times are obtained for a 2 minute delay in addition of Mighty-150. It is of interest that the 2 minute delay in the 5 minute continuous mix cycle offered longer working times than the 6 minute delay in the ASTM 3-3-2 cycle. The total working time of 44 minutes might be usable in practice, provided haul times were short and no delays on the site were encountered.

5. Simulation of Field Mix Cycles

As mentioned in the previous section, the ASTM 3-3-2 mix cycle is not representative of the mixing times currently used in actual practice. As mix time (as it relates to time of addition of SWR) was seen to have a large effect on slump loss

characteristics, further work with more typical mix cycles was warranted. It was recognized that the laboratory mixers are not accurate simulations of full scale central mixers or R-M trucks, and that there may be other problems inherent in the production of large volumes of concrete which would not be apparent in the small lab mixers. However, relative differences between admixtures and between various cement/admixture combinations should still be evident in the smaller mixers.

The two cycles chosen as being most typical of actual production were termed "central-mix" (C-M) and "ready mix" (R-M). The C-M cycle consisted of a 60 or 90 sec. mix, no remixing was used. This mixing time was chosen so as to fall within the recommendations of ACI 316-74[1/], which requires a minimum mixing time of 50 sec.

Coversations with local concrete producers indicated that the maximum mixing time in C-M operations was 90 sec., thus the choice of the 60 or 90 sec. mixes for this phase of the project. As C-M concrete is generally transported to job sites in non-agitating bodies, no remixing after the 90 sec. original mix was used. The R-M cycle consisted of an initial 3 minute mix during which the A/E agent and all mix water was added. This was followed by a 20 minute delay, at which time the SWR was added and the concrete remixed for 60-90 sec. The concrete was then remixed for 30 sec. every 10 minutes.

of the SWR (Mighty-150 and Melment L-10) using a typical central-mix cycle. Concretes were prepared at varying dosages of SWR and varying initial slump levels. In addition, other admixtures were tried in combination with SWR in order to combat the slump loss problem. Strength and durability characteristics of the most promising mixes were evaluated.

5.1.1 Control Mixtures

Control concretes for the C-M simulations were similar to those used in the previous work. Aggregate gradation and physical properties are given in Table 10 (page). A new lot of Type I cement (No. 21802) was obtained from the same supplier from which lot No. 21795 was purchased. Chemical composition was similar, but not identical (see Appendix D). Concretes were designed for a nominal cement factor of 564 lb/yd^3 (335 kg/m^3), slump of 2-3 inches (51-76 mm), and air content of 5 ± 1%. Actual mixture proportions are shown in Table 18A, along with characteristics of the fresh concrete (Table 18B).

5.1.2 Initial Mixtures Using SWR

Mighty-150 and Melment L-10 were added to the C-M concretes so as to obtain a w/c ratio of 0.35 while maintaining initial slump levels of 2-3 inches (51-76 mm). Two addition sequences were employed. In the first, the SWR was added to the mix water and the A/E agent was added after 20 sec. of mixing. The total mixing time

TABLE 18A

Concrete Mixture Proportions

C-M Controls

		Quantities lb per cu yd - SSD[1/]				%	
No.	Description	Water	Cement	Sand	Coarse Aggregate	Sand Abs. Vol.	A/E Agent (ml/lb cement)
C-1	Central Mix-Type I Cement	259	562	1,228	1,821	40	3.9

1/ To convert from lb/yd^3 to kg/m^3 multiply by 0.594

5.1 Central Mix (C-M) Operations

The objective of this task was to evaluate the slump loss characteristics of two

1/ "Recommended Practice for Construction of Concrete Pavements and Concrete Bases", ACI 316-74

in this instance was 60 sec. In the second sequence of admixture addition, (-D), the NVR was added 10 sec. after initiation of mixing, then the SWR was added at 30 sec. and mixing continued for a total of 90 sec. Properties of the fresh concretes are given in Table 19. As seen in the earlier work, the delay in

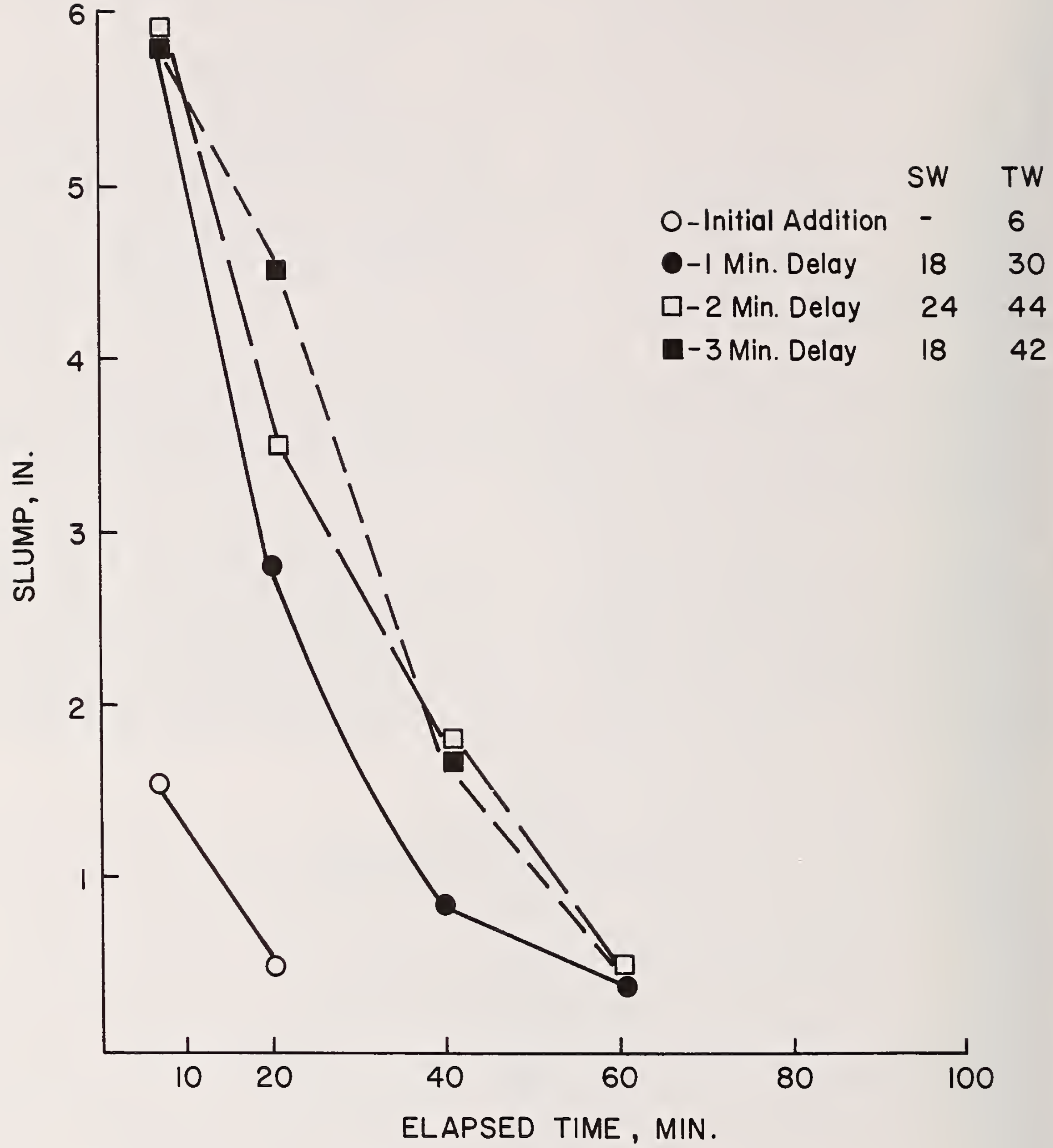

FIGURE 28. SLUMP LOSS IN BRIDGE DECK MIXTURES WITH MIGHTY-150. 5 MINUTE MIX CYCLE

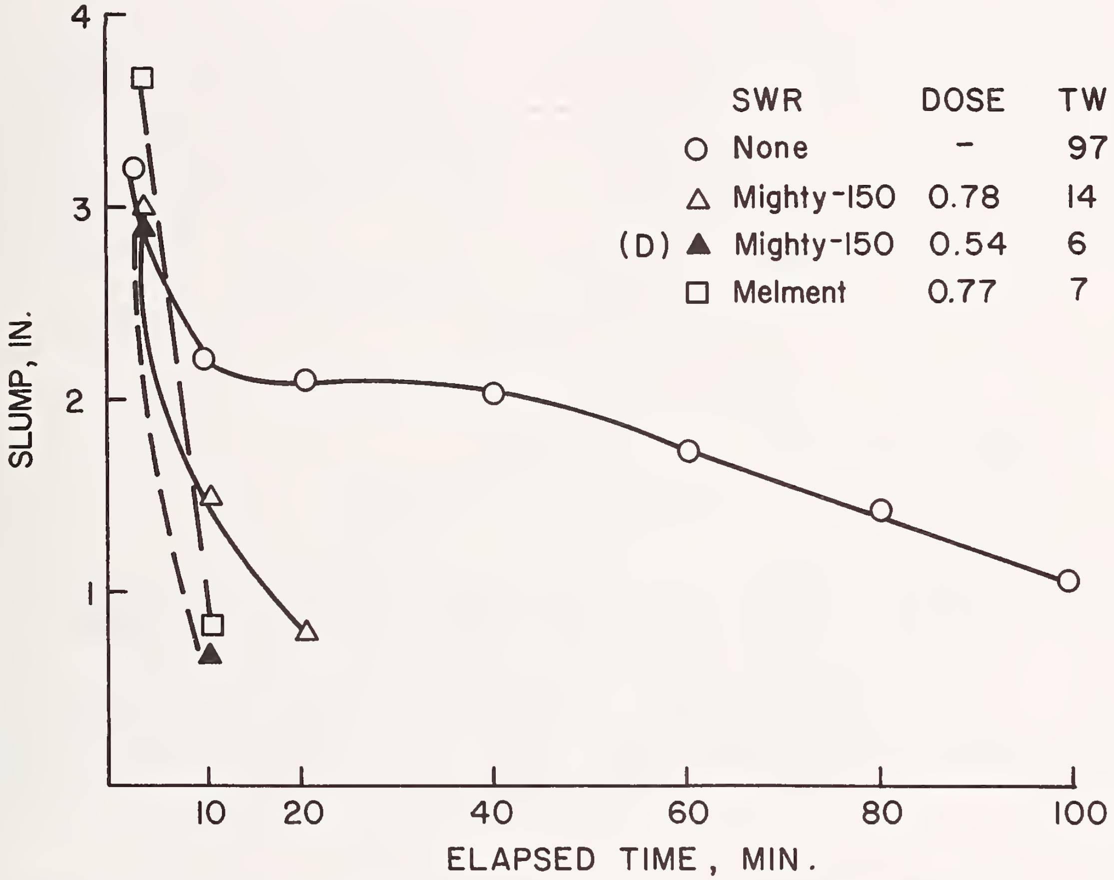

FIGURE 29. SLUMP LOSS IN CENTRAL-MIX BATCHES

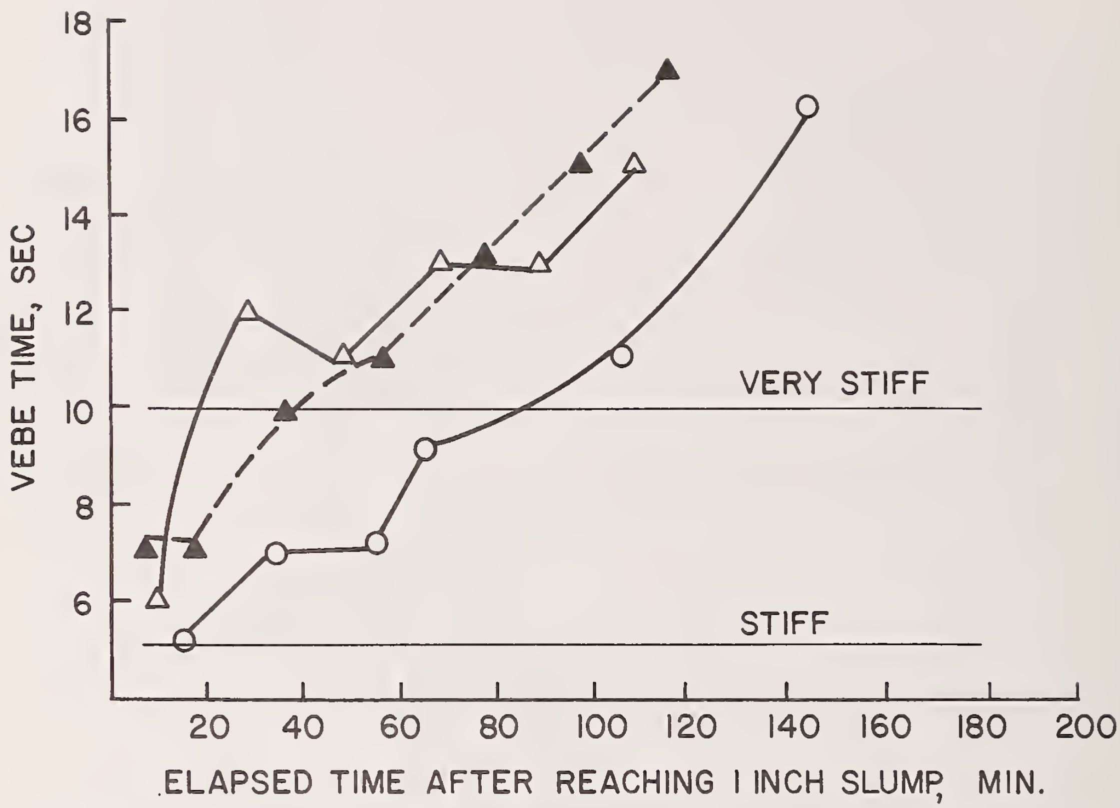

FIGURE 30. INCREASE IN VEBE TIME FOR CENTRAL-MIX BATCHES

TABLE 18B

Characteristics of Fresh Concrete
C-M Controls

No.	w/c	Slump (in.) 1/	Air Content (%)	Unit Weight lb/cu ft 2/
C-1	0.46	3.2	4.9	143

1/ To convert from inches to mm multiply by 25.4.
2/ To convert from lb/cu ft to kg/m^3 multiply by 16.038.

addition of SWR allows one to substantially reduce the amount of admixture needed to obtain a given slump. The amount of A/E agent needed to obtain the specified air content was less than that for control mixtures when Mighty-150 was used and essentially the same as for control mixtures when Melment L-10 was used.

rheology. Thus, one supposedly need not be concerned with the apparent stiffness of such mixes as placement would still be easier than with a conventional mix of equal slump. To check this possibility the mixtures were tested in a Vebe Consistometer(12) beginning at the point where the concrete fell below 1 inch (25 mm) of slump. Results are shown in Figure 30. The abscissa expresses the time elapsed after the concrete reached one inch (25 mm) of slump, in order to translate all the curves onto a common axis. In real time, the control plot would be initiated at approximately 100 minutes after mixing, the SWR plots at approximately 10-20 minutes after mixing. The plots indicate that there is no benefit derived from the presence of the residual SWR in the low-slump concrete, in fact, the rate of increase in "Vebe time" is greater for the mixes containing SWR. The higher rate of slump loss thus translates into a correspondingly higher rate of "Vebe gain," and the mixtures containing SWR reach the very stiff consistency level more rapidly then the control.

TABLE 19

Properties of Fresh Concrete

C-M Batches

Mighty-150 and Melment L-10

No.	SWR	Dose (% s/c)	A/E Agent (ml/lb cement)	w/c	Slump (in.) 1/	Air Content (%)	Water Reduction (%)
CM-1	Mighty-150	0.78	1.4	0.35	3.0	5.6	23.6
CM-1D	Mighty-150	0.54	2.2	0.35	2.9	5.7	23.6
CL-1	Melment L-10	0.77	3.8	0.35	3.7	6.0	23.6

1/ To convert from inches to mm multiply by 25.4.

Slump loss characteristics for these mixtures are shown in Figure 29. The high rates of slump loss seen in the SWR mixtures confirm similar losses seen in the earlier work. In this case, somewhat higher rates are seen when Mighty-150 is added using a 30 sec. delay as compared to when it is added to the initial mix water. In both cases, however, the slump loss rates are intolerable from an applications standpoint.

Some undocumented reports have indicated that even though concretes containing SWR lose slump rapidly, their response to vibration at low slumps (less than 1 inch (25 mm)) is better than that of conventional concretes, presumably due to a residual effect of SWR on the paste

5.1.3 Use of Accelerators in Mitigating Slump Loss

Paradoxically, the use of chemical accelerators may offer a means of reducing slump loss. It was hypothesized that if the cement hydration rate could be accelerated, then less SWR would be adsorbed onto the unhydrated cement particles and more would be available for maintenance of the dispersed condition. Two accelerators, anhydrous calcium chloride ($CaCl_2$) and triethanolamine (TEA) were chosen for investigation. They were added to the mix water of Mixture CM-1 in amounts varying from 0.05% to 1% by weight of cement. The accelerator was added to a small portion of the initial mix water in a stainless steel beaker.

In the case of anhydrous $CaCl_2$, the beaker was cooled under tapwater while adding the $CaCl_2$. This solution was then added to the remaining mix water. NVR was added after 10 sec. of mixing, and Mighty-150 was added at a dosage rate of 0.5% s/c after 30 sec. of mixing. Results are given in Table 20.

Although a significant increase in total working time was seen for 0.05% $CaCl_2$, this was not reproducible in a later duplicate test. TEA only increased working times by a few minutes. These results indicate that although there is an effect of decreased slump loss when accelerator is added, which has some theoretical interest, the increase in working times obtained via this approach are not great enough to allow for transport of the concrete to a job site.

TABLE 20

Effect of Chemical Accelerators on Slump Loss Characteristics

Central-Mix - Mighty-150

Accelerator	Dosage (% s/c)	Initial Slump (in.) 1/	Total Working Time (min)
None	-	2.9	6
$CaCl_2$	1	3.1	4
$CaCl_2$	0.5	3.0	7
$CaCl_2$	0.1	3.4	15
$CaCl_2$	0.05	3.8	22
$CaCl_2$	0.05	3.5	8 2/
TEA	0.3	2.8	5
TEA	0.1	4.3	12

1/ To convert from in. to mm multiply by 25.4.
2/ Duplicate run

5.1.4 Use of Higher Dosage Rates of SWR

In the previous section it was seen that a delay in addition of SWR by a few minutes would result in higher initial slumps and longer working times. This was believed due to the ability of the cement to partially hydrate prior to addition of the SWR, thus there is more admixture in solution available for water reduction. In the central-mix situation, however, a few minutes delay would be unacceptable to most producers. An alternative method of decreasing slump loss would be to simply increase the amount of SWR added initially. Although more costly, this might allow sufficient working times such that the concrete could be placed up to 45 minutes after mixing (the maximum allowed by ACI 316-74). In this task the use of such higher dosage rates was investigated.

Mixtures were prepared having design identical to CM-1. Mighty-150 was then added at dosages up to 1.0% s/c. For most of these tests Mighty-150 was added at a 30 sec. delay, but for two tests initial addition (i.e., SWR added to mix water) was tried. As all slump loss plots were relatively similar in shape, results are shown in Tabular format Table 21).

TABLE 21

Slump Loss Characteristics

Increasing Dosages of Mighty-150

C-M Batches

Dose (% s/c)	Addition Time	Initial Slump (in.) 1/	Slump Window (min)	Total Working Time (min)
0.54	30 sec.	2.9	-	5
0.64	30 sec.	4.8	12	16
0.74	30 sec.	5.1	14	18
0.78	Initial	3.0	-	14
0.84	30 sec.	5.0	8	14
1.0	30 sec.	5.7	13	22
1.0	Initial	5.6	18	30

1/ To convert from in. to mm multiply by 25.4.

The results show that relatively high dose rates of Mighty-150 are needed if working times close to 1/2 hour (a practical <u>minimum</u> for paving operations) are to be achieved. As these dosages (1.0% s/c) are considerably above the recommendations of the manufacturer, some retardation of set might be expected. Severe retardations might pose a problem with delay of such operations as edging, setting of construction joints, and texturing. Setting times for a number of these mixtures were determined using a modification of ASTM C403-77 1/, which consisted of use of a mortar mixture prepared using the same aggregate gradation as in the concrete, but excluding all aggregate greater than that which passes the No. 4 (4.75 mm) sieve. This was done in lieu of wet-screening of a full concrete batch. Although results

1/ ASTM C403-77, "Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance."

are somewhat different using this technique, more batches can be tested on a single day and relative differences between control and admixtured concretes can be found.

The results (Table 22) show that at the highest dosages employed, significant retardation in initial and final set times are evidenced. Addition of calcium chloride to these mixtures at a rate of 0.1% by weight of cement alleviates this problem somewhat, but slump loss was then found to increase back to the level of the mixture prepared with 0.70% Mighty-150 and no accelerator (total working time = 14 minutes). The retardations seen at higher dosages of Mighty-150 might be tolerable on some jobs where finishing operations were minimal, provided that strength development was not impaired. Compressive strengths measured on 6x12-inch (152x 305 mm) cylinders cast from these mixes are given in Table 23.

strengths typical of low water-cement ratio concretes. Increasing amounts of Mighty-150, however, reduce these strength levels substantially. At 1.0% s/c strengths are little better than those of the controls, defeating the purpose of using the SWR.

A limited amount of work was done with the melamine-based product, Melment L-10 in similar mixtures. Dosages, properties of fresh concretes, slump loss characteristics, and setting times are shown in Table 24.

Note that even at very high dosages of Melment L-10, total working time is less than 18 minutes. Retardation of mixtures utilizing Melment L-10 is less than in mixtures containing Mighty-150. The two parameters of slump loss and retardation appear to be related. That is, higher rates of slump loss imply less retardation. Decreasing the rate of slump loss by adding more SWR results in greater

TABLE 22

Setting Time of Concretes Containing Various Dosages of Mighty-150

Dosage (% s/c) Mighty-150	$CaCl_2$	Setting Time (hr:min) Initial	Final	Retardation (hr:min) Initial	Final
-	-	3:35	4:55	-	-
0.54*	-	4:40	6:25	1:05	1:30
0.78	-	4:30	6:20	0:55	1:25
1.0	-	6:00	7:25	2:25	2:30
1.0	0.1	5:25	6:40	1:50	1:45

*30 second delayed addition

TABLE 23

Compressive Strength of Concretes Containing Various Dosages of Mighty-150

Dosage (% s/c)	Compressive Strength, psi 1/ 1d	3d	28d
None	-	3,040	5,550
0.78	-	5,170	7,600
0.85	2,670	4,390	6,820
0.93	2,220	3,590	5,900
1.00	2,420	3,480	5,900

1/ To convert from psi to MPa multiply by 0.0069.

TABLE 24

Properties of C-M Batches Prepared with Melment L-10

	Dosage (% s/c) 0.77	1.34	None
Slump, in. 1/	3.7	6.0	3.2
Air Content, %	6.0	5.0	4.9
Slump Window, min.	4	10	-
Total Working Time, min.	6	18	97
Initial Set, hr:min.	3:23	4:10	3:35
Final Set, hr:min.	4:50	5:40	4:55

1/ To convert from in. to mm multiply by 25.4.

The specimens containing the lowest dosage (0.78% s/c) show the high

retardations. Overcoming this retardation by adding an accelerator re-introduces the slump loss problem.

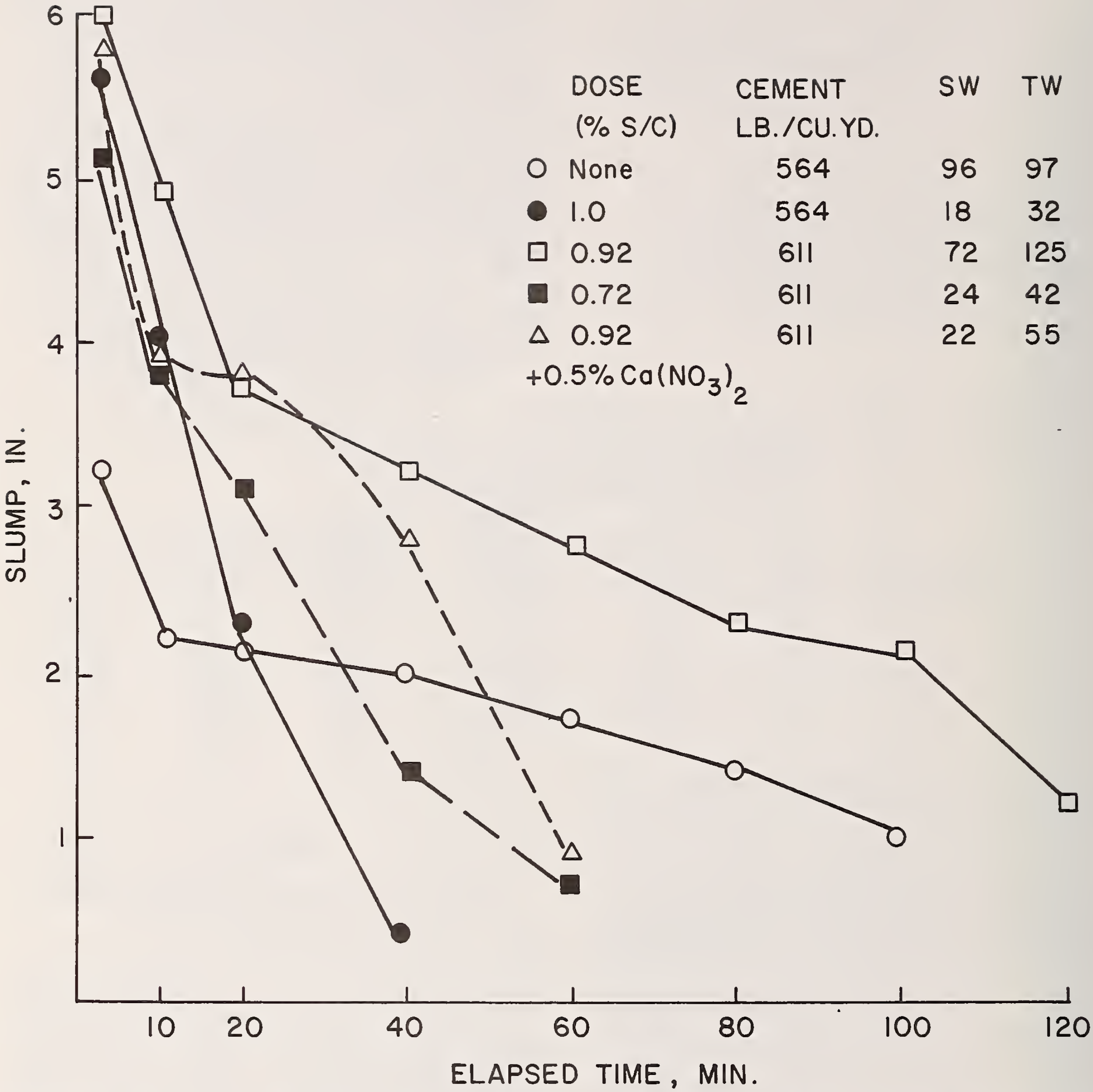

FIGURE 31. SLUMP LOSS IN CENTRAL-MIX BATCHES USING INCREASED AMOUNTS OF MIGHTY-150

5.1.5 Use of Increased Paste Content

The high rates of slump loss seen in the C-M batches are due, in part, to the reduction in paste content brought about by reduction in the net mix water of approximately 24%. The paste content in the "pavement" mix design is already low due to the use of 1.5-inch (38 mm) maximum size aggregate. Removal of what amounts to 14% of the paste volume coupled with the loss of SWR efficiency with time due to chemical effects results in very rapid slump loss. It was felt that an increase in paste content (maintaining water-cement ratio while increasing cement content) would increase the interparticle distance, reduce internal friction, and thus somewhat offset the inherent slump loss due to admixture/cement interaction.

A number of mixtures were prepared using 611 lb/yd^3 (363 kg/m^3) of cement at a water-cement ratio of 0.35. Various dosages of Mighty-150 were used. In all cases, Mighty-150 was added to the initial mix water, NVR was added at 20 sec. and the total mixing time was 60 sec. Plots of slump as a function of time for these, as well as control (no admixture), and a mixture with cement content of 564 lb/yd^3 (335 kg/m^3) containing 1.0% (s/c) Mighty-150 are shown in Figure 31. The mixtures prepared at higher paste contents show a definite improvement in slump loss characteristics. The best results are achieved at a dosage of 0.92% s/c, but data in Table 23 indicate that this amount of admixture will reduce the rate of strength gain. Use of 0.72% Mighty-150 coupled with the increased paste content should yield acceptable strength levels, but slump loss is increased. Addition of 0.5% calcium nitrate ($CaNO_3$), a chloride free accelerator, improves the strength properties and yields a total working time of <u>almost 1 hour</u>.

The sensitivity of the slump loss curves with respect to small changes in admixture content, the increased amount of cement needed, and the difficulties in controlling the additions of three admixtures make this approach strictly a laboratory exercise at this time. Based on all available data, it must be concluded that application of super water-reducing admixtures to traditional paving operations will be extremely difficult. Barring radical changes in admixture composition which will offset slump loss, <u>the use of these admixtures in paving operations utilizing central mixing and non-agitating transport cannot be recommended</u>.

5.2 Ready-Mix (R-M) Operations

When smaller volumes of concrete than used in a complete paving job are required, ready-mix trucks are usually employed. This area offers more potential for the use of SWR, as the admixture can be added on-site, thus eliminating much of the slump loss which would occur in transit.

The objective of this task was to evaluate slump loss characteristics of mixtures typical of those used in bridge deck construction. The on site addition of SWR was simulated by waiting for various times after the completion of the initial mix period before addition of admixture. As the addition of more than one admixture on the job site can cause much confusion, the A/E agent was added to the initial mixture.

5.2.1 Control Mixtures

Control mixtures for the R-M simulations were similar to those used for the "bridge deck" mixtures used in the earlier work. Aggregate gradations and physical properties are given in Table 10 (page 31). Cement lot No. 21802 was used for all mixtures. Concretes were designed for a nominal cement content of 658 lb/yd^3 (391 kg/m^3), slump of 2-3 inches (51-76 mm) and air contents of 6-7%. Mix proportions and characteristics of the fresh concrete are shown in Tables 25A-25B.

TABLE 25A

Characteristics of Fresh Concrete
R-M Controls

No.	w/c	Slump (in.) 1/	Air Content (%)	Unit Weight (lb/cu ft) 2/
R-1	0.42	3.2	6.3	143

1/ To convert from in. to mm multiply by 25.4.
2/ To convert from lb per cu ft to kg/m^3 multiply by 16.038.

5.2.2 Mixtures Containing SWR - Conventional Initial Slump

The SWR Mighty-150 and Melment L-10 were added to concretes having design similar to R-1, but with sufficient water removed to lower the water-cement ratio below 0.35. In all cases, the SWR was added in the "delay mode" that is after the

TABLE 25B

Concrete Mix Proportions

R-M Controls

No.	Description	Water	Cement	Sand	Coarse Aggregate	% Sand Abs. Vol.
		Quantities lb per cu yd - SSD[1/]				
R-1	Ready Mix - Type I Cement	277	659	1,166	1,749	40

1/ To convert from lb/cu yd to kg/m^3 multiply by 0.594.

initial 3 minute mix had been completed. As the A/E agent (NVR) was added to the initial mix, its efficiency was greatly reduced and much more agent was needed than in control mixtures. Properties of fresh concretes, including SWR and A/E agent dosages are given in Table 26, setting times are shown in Table 27.

It is easily seen that dosages of SWR needed to obtain slump levels equal to the control are less for these mixtures than for the central-mix series. Water reductions are slightly less due to the fact that control R-M batches are at a lower initial water-cement ratio than

TABLE 26

Characteristics of Fresh Concrete

R-M Batches

No.	SWR	Dose (% s/c)	Delay Time (min.)	A/E Agent (ml/lb)[1/]	w/c	Slump (in.)[2/]	Air Content (%)	Unit Weight[3/] (lb/cu ft)	Water Reduction (%)
RM-1A	Mighty-150	0.37	20	9.8	0.34	3.7	5.9	147	19.9
RM-1B	Mighty-150	0.40	40	10.7	0.34	3.3	5.4	147	19.1
LR-1	Melment L-10	0.44	20	18.0	0.34	3.4	6.6	146	20.2

1/ To convert from ml/lb to m/kg multiply by 2.20.
2/ To convert from in. to mm multiply by 25.4.
3/ To convert from lb/cu ft to kg/m^3 multiply by 16.038.

TABLE 27

Setting Times of R-M Concrete Containing Various Dosages of Mighty-150 and Accelerators

Mighty-150 Dosage (% s/c)	Accelerator	Dosage (% s/c)	Setting Time (hr:min) Initial	Setting Time (hr:min) Final	Retardation (hr:min) Initial	Retardation (hr:min) Final
-	Control	-	4:00	5:10	-	-
0.37	None	-	4:40	6:00	0:40	0:50
0.46	None	-	5:40	7:45	1:40	2:35
0.46	$Ca(NO_3)_2$	0.5	4:35	6:10	0:35	1:00

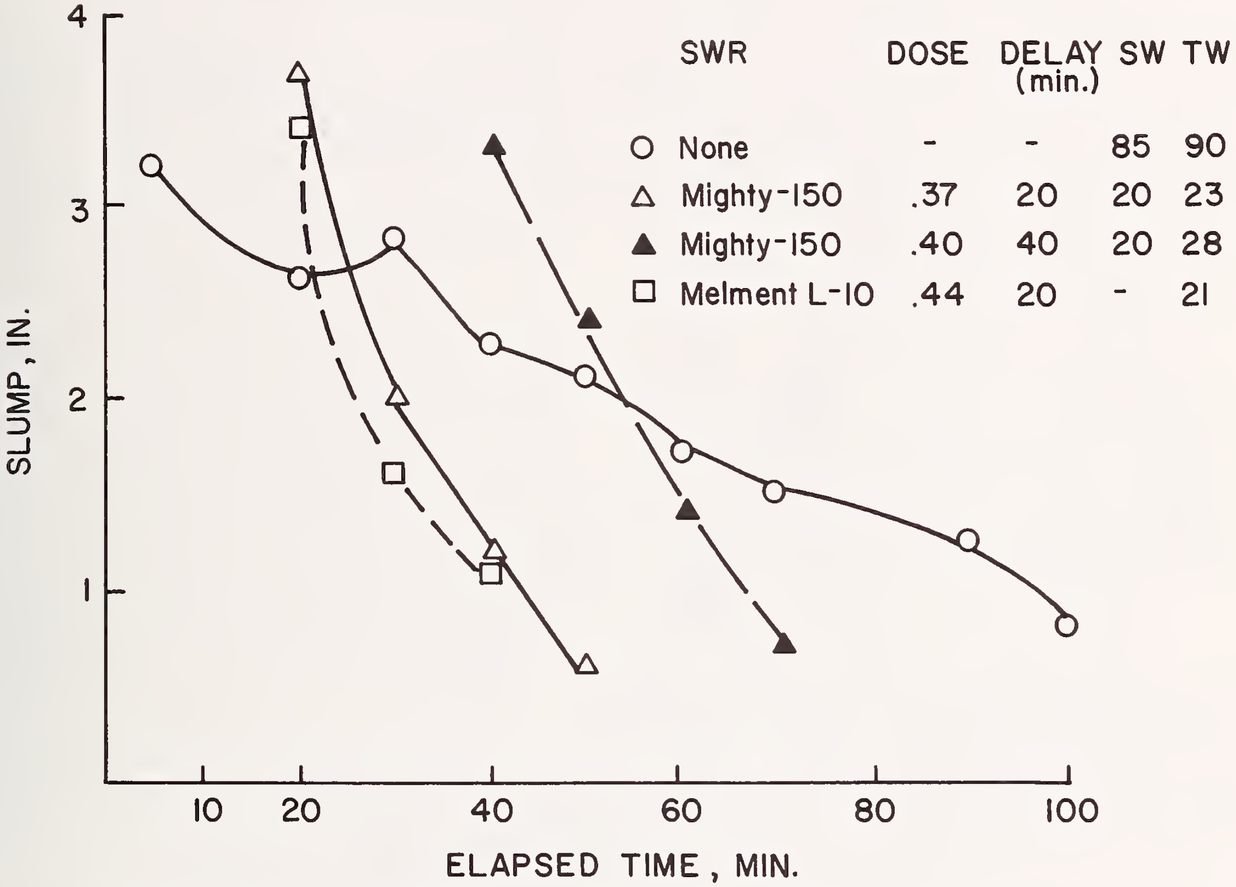

FIGURE 32. SLUMP LOSS IN READY-MIX BATCHES

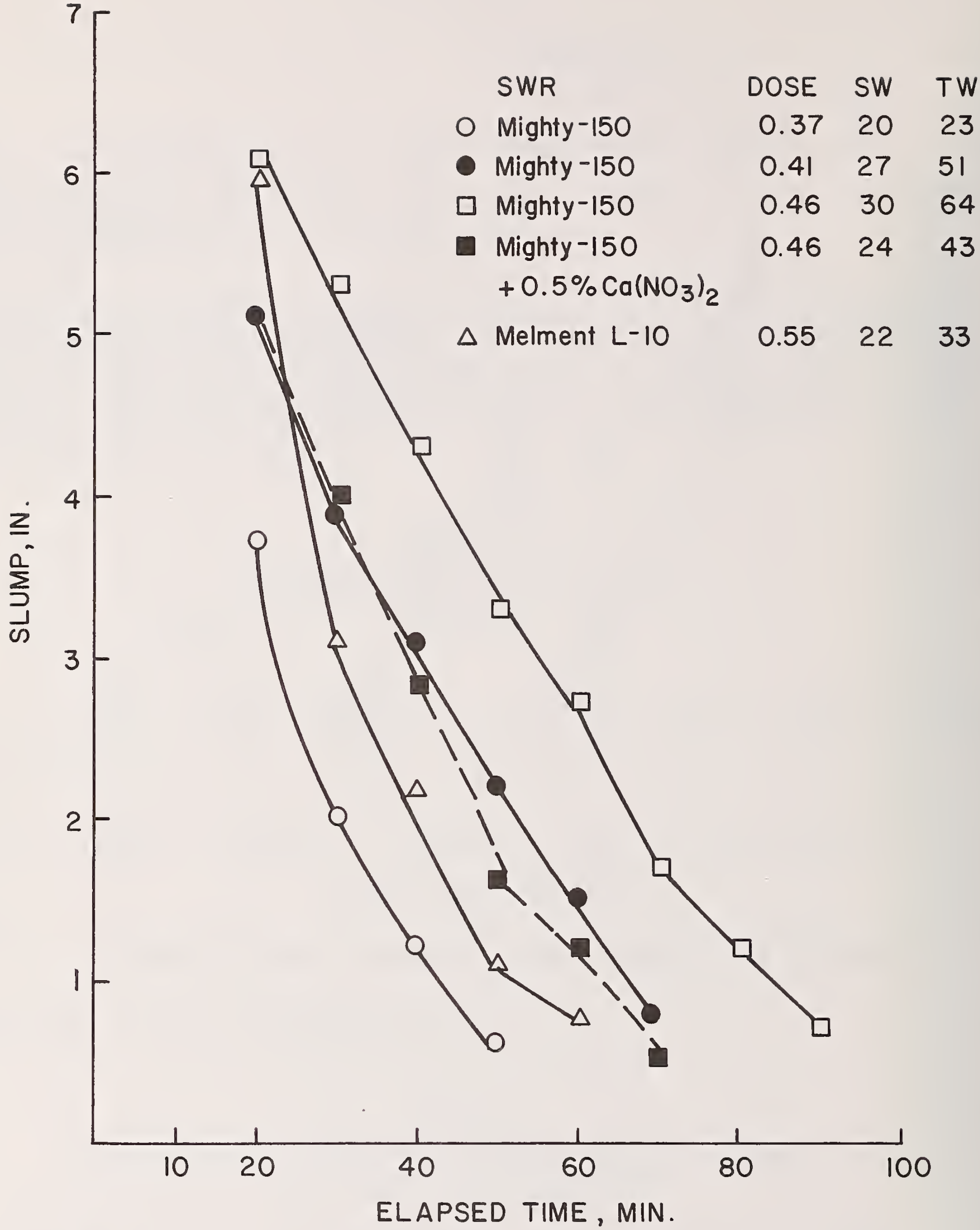

FIGURE 33. SLUMP LOSS IN READY-MIX BATCHES USING INCREASED AMOUNTS OF MIGHTY-150

control C-M batches (0.46 for C-M vs. 0.42 for R-M).

The lower SWR dosage requirements for these mixes as compared to the C-M batches can be attributed to three major factors:

1. The control for R-M is at a lower water-cement ratio than the control for C-M, thus less water reduction is necessary to reach an equivalent water-cement ratio.

2. The delayed addition of SWR improves their efficiency. Less SWR is needed to reach a given slump when added in the delayed mode.

3. The higher cement content of the R-M concrete improves the efficiency of the SWR.

Slump loss for these mixtures is depicted in Figure 32. All batches were remixed for 30 sec. prior to the slump determinations at 10 minute intervals. A comparison with the slump loss profiles for the C-M batches (Figure 29) shows that although the control mixtures exhibit very similar rates of slump loss, the working times for the admixtured batches are greater in the R-M case. This is especially apparent for the Melment L-10 mixtures, the R-M batches showing total working times three times longer then the C-M batch.

Although working times are greater for the R-M batches, 20 minutes is still on the low side in terms of actual operations. Based on the results of previous tests, increased dosage of SWR appeared to offer a good means of achieving longer working times. Slump loss curves for batches containing increasing dosages of SWR are shown in Figure 33. Also included are slump loss data for a batch to which 0.5% of calcium nitrate was added as a set accelerator. This was done after time-of-set data (Table 27) indicated retardations at the higher dosages. The use of the accelerator, however, decreased the working time from 64 minutes without accelerator to 43 minutes with the accelerator. It is also evident that the mixture containing 0.55% Melment, while starting at a slump equal to that of the mixture containing 0.46% Mighty-150, exhibited more rapid slump loss.

These data indicate that super water-reducers have the capability for producing low water-cement concrete for R-M operations in the highway field. It is necessary, however, to increase initial slump levels to 5-6 inches (127-152 mm) in order to gain sufficient time in which to place and consolidate the concrete, even when the SWR is added in delayed addition mode at the job site. As the amount of SWR necessary to achieve these levels may cause some amount of retardation, small amounts of accelerator can be added to the concrete in order to overcome this effect.

5.3 Overlay ("Iowa") Mixtures

In response to the need for a more impermeable concrete to resist penetration of deicing salts to bridge deck reinforcing mats a high cement content, low water-cement ratio mixtures have been developed (13). Known as the "Iowa Method," the concrete mixture is typically designed for 820 lb/yd^3 (487 kg/m^3) of cement, a water-cement ratio of 0.32, slump of 1/2 to 1 inch (13-25 mm), and air content of 6.5 ± 1/5%. A conventional water reducer is often used to impart a limited amount of workability to the mixture, but even so, heavy vibration is needed to achieve adequate consolidation. It was felt that this would be an ideal applications area for super water reducers, which could be added to the relatively low slump mixture for purposes of increasing the workability while maintaining the same low water-cement ratio as in the conventional "Iowa" design.

Mix design is given in Table 28A. As the SWR were used to impart workability, and not to further reduce water, the designs for the mixtures containing the SWR are essentially the same as for the control. Properties of fresh concretes, including controls, are shown in Table 28B. All SWR were added using a 20 min. delay.

A comparison with dosages for R-M batches (Table 26) indicates that considerably less SWR is needed for the overlay mixtures. This can be attributed to the higher cement content and to the fact that the overlay mixtures exhibited measurable, though low, slump prior to addition of SWR. The R-M and C-M batches were initially at zero, or negative slump, thus more admixture would be needed to increase the slump to 3 inches (76 mm).

Slump loss curves are shown in Figure 34. In spite of the fact that initial slumps were in the 2-3 inch (51-76 mm) range, where previous mixtures containing SWR has exhibited very high slump loss rates, in the case of the overlay mixtures slump loss is not as great. For the Mighty-150 mixture a working time of 44 minutes is indicated, which should be sufficient for practical applications. Setting time

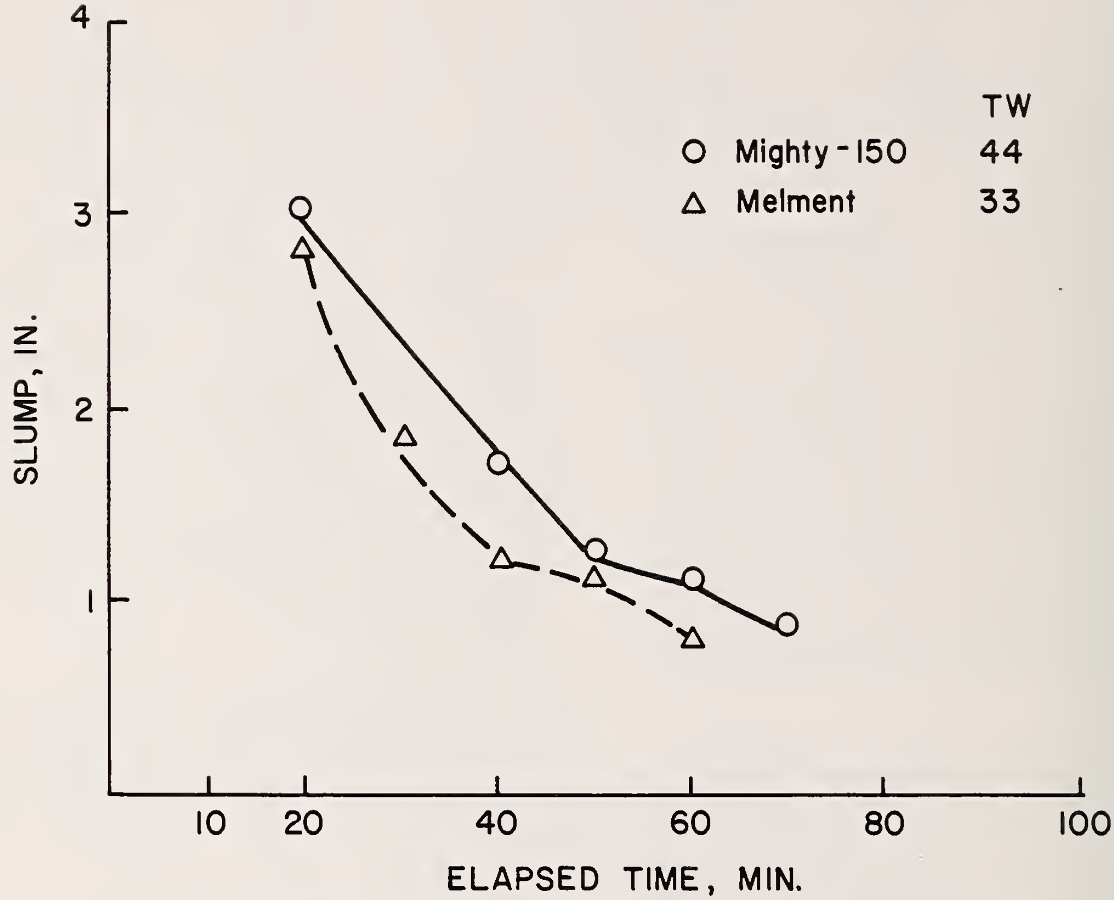

FIGURE 34. SLUMP LOSS IN OVERLAY BATCHES

TABLE 28A

Concrete Mix Proportions

Overlay ("Iowa") Mixtures

No.	Description	Quantities lb per cu yd - SSD 1/ Water	Cement	Sand	Coarse Aggregate	% Sand Abs. Vol.
I-1	Overlay - Type I Cement	279	828	1,391	1,391	50

1/ To convert from lb/yd^3 to kg/m^3 multiply by 0.594.

TABLE 28B

Characteristics of Fresh Concrete

Overlay ("Iowa") Batches

No.	SWR	Dosage (% s/c)	A/E Agent (ml/lb) 1/	Slump (in.) 2/	Air Content (%)	Unit Weight (lb/cu ft) 3/
I-1	None	-	9.9	0.8	5.9	144
IM-1	Mighty-150	0.16	10.6	3.0	5.9	144
IL-1	Melment	0.14	10.6	2.8	6.5	143

1/ To convert from ml/lb to m/kg multiply by 2.20.
2/ To convert from inches to mm multiply by 25.4.
3/ To convert from lb/cu ft to kg/m^3 multiply by 16.038.

data on these mixtures are given below. Some retardation is shown for the Mighty-150 and Melment mixtures, but severe retardation is not indicated.

TABLE 29

Setting Times of Overlay ("Iowa") Mixtures

SWR	Dosage	Setting Time (hr:min) Initial	Setting Time (hr:min) Final	Retardation (hr:min) Initial	Retardation (hr:min) Final
None	-	2:40	3:55	-	-
Mighty-150	0.16	3:40	4:40	1:00	0:45
Melment L-10	0.14	3:20	4:45	0:40	0:50

These results indicate that problems with rapid slump loss should not be as great in high cement content "Iowa" mixtures used for overlay applications. SWR could be added at the jobsite to a R-M agitating truck, or as an alternative, a mobile concrete mixer could be used to mix all materials on site. The second approach will be considered in a later section of this report.

6. Effects of Temperature on Slump Loss

All work in the program to this point, including slump loss testing of pastes and concretes, had been carried out at ambient laboratory temperatures of 73 ± 2°F (23 ± 1°C). In actual use, tempera tures during concrete operations may vary over a considerable range. The objective of this portion of the program was to evaluate the effects of temperatures in the range of 45°F (7°C) to 90°F (32°C) on the slump loss and setting times of both controls and mixtures containing SWR. All batching mixing and testing was carried out at nominal temperatures of 45°F, 60°F, 73°F, and 90°F (7°C, 16°C, 23°C, and 32°C). Temperature was controlled to within ± 2°F (± 1°C) of the nominal value. As no provisions were available for control of relative humidity at any temperatures other than 73°F (23°C), the mixer pan was fitted with a rigid lucite cover so as to reduce evaporation losses to a minimum. No attempt

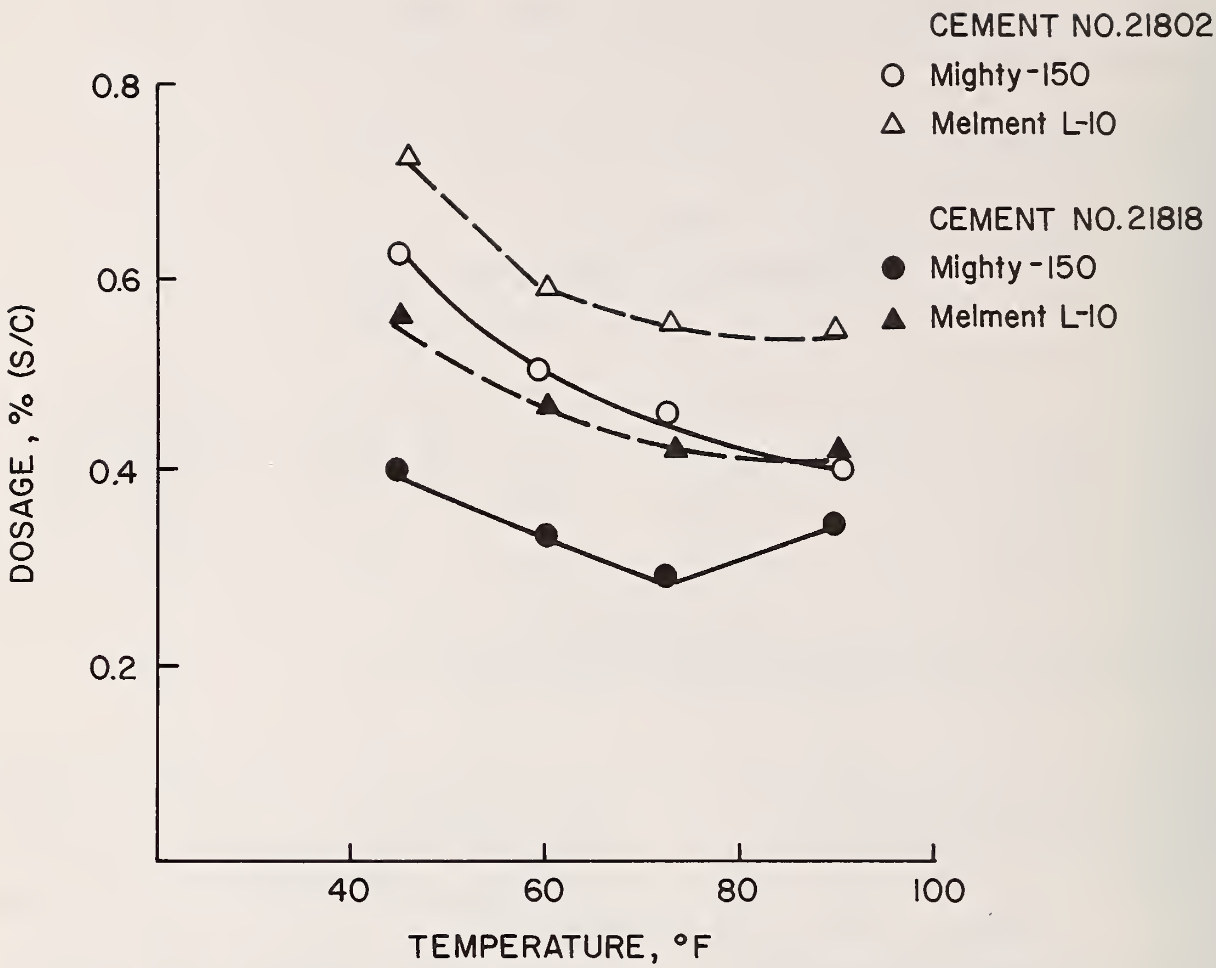

FIGURE 35. DOSAGE OF SUPER WATER REDUCERS AS A FUNCTION OF TEMPERATURE

was made to simulate the use of such field procedures as heating of aggregates in cold weather or addition of ice to mixtures in hot weather, although it is recognized that such procedures are often used when appropriate equipment is available.

In addition to the Type I cement used in the previous tasks (Lot No. 21802) a second cement was added to this portion of the study. This cement (Lot No. 21818) was found to have a significantly lower requirement for SWR on the basis of the mini-slump results. The lower dosage requirement for this cement can be attributed to its lower C_3A, and lower Blaine fineness as compared to cement No. 21802.

6.1 Control Mixtures

The concrete mixtures used corresponded to the "bridge deck" mixtures described on page 31. Control concretes were designed for a cement content of 658 lb/yd^3 (390 kg/m^3), slump of 2-3 in. (50-80 mm) and air content of 6 ± 1/2%. Water content and air-entraining agent (NVR) dosage were adjusted at the various temperatures to achieve the desired parameters. Properties of the freshly-mixed control concretes are given in Table 30.

6.2 SWR Mixtures

Concretes containing SWR were designed for equal cement content to those of the controls, and the w/c ratio was fixed at 0.35. Dosages of SWR were

Table 30A

Control Mixtures

Cement No. 21802

	Temperature - °F 3/			
	45	60	73	90
Cement (lb/yd^3) 1/	656	652	656	652
Water (lb/yd^3) 1/	288	285	292	287
w/c Ratio	0.44	0.44	0.44	0.44
Slump (in.) 2/	2.0	3.3	2.3	3.0
Air Content (%)	6.1	6.3	6.0	6.3
A/E Agent (ml/lb)	1.9	2.5	3.3	4.6

1/ To convert from lb/yd^3 to kg/m^3 multiply by 0.594.
2/ To convert from in. to mm multiply by 25.4.
3/ °C = 5/9(°F - 32).

Table 30B

Control Mixtures

Cement No. 21818

	Temperature - °F 3/			
	45	60	73	90
Cement (lb/yd^3) 1/	658	656	663	663
Water (lb/yd^3) 1/	277	260	277	280
w/c Ratio	0.42	0.40	0.42	0.42
Slump (in.) 2/	3.4	2.6	3.4	2.8
Air Content (%)	6.0	6.3	5.4	5.4
A/E Agent (ml/lb)	1.3	2.1	1.7	2.1

1/ To convert from lb/yd^3 to kg/m^3 multiply by 0.594.
2/ To convert from in. to mm multiply by 25.4.
3/ °C = 5/9(°F - 32).

adjusted so as to achieve an initial slump of 6 ± 1/2 inch (152 ± 13 mm). The SWR was added in the delayed addition mode at 20 minutes after an initial mix period of 3 minutes. Admixture dosage requirements and characteristics of fresh concretes containing SWR at the various temperatures are shown in Table 31 for cement No. 21802 and in Table 32 for cement No. 21818.

It is easily seen that the A/E agent requirements for these mixtures are much greater than for the controls. This is obviously attributable to the type of addition sequence chosen, the A/E agent being added to the "dry" (no SWR added) mixture. It is only after the 20 minute delay and subsequent addition of SWR that the air void system is developed. For the first cement, the A/E agent dosage requirement is higher for the Melment mixtures than for the Mighty-150 mixtures at all temperatures. For the second cement the A/E agent requirements are essentially the same for the Mighty-150 and Melment mixtures.

Dosage requirements needed to obtain an initial slump of approximately 6 in. (150 mm) are plotted vs. temperature of mixing in Fig. 35. It can be seen that dosage rises with a decrease in temperature below 73°F (23°C). This may result from the fact that the SWR in this study were added 20 minutes after the start of mixing. It is known (2) that a delay in addition will increase the effectiveness of chemical admixtures at constant temperature, presumably due to the onset of

Table 31

Characteristics of Fresh Concretes

Cement No. 21802

	Temperature - °F 2/			
	45	60	73	90
1. Mighty-150 Mixtures				
Cement (lb/yd^3) 1/	649	647	651	652
Water (lb/yd^3) 1/	229	228	230	230
w/c Ratio	0.35	0.35	0.35	0.35
Mighty-150 (% s/c)	0.62	0.50	0.46	0.41
A/E Agent (ml/lb) 3/	11.5	10.7	11.3	16.2
Slump (in.) 4/	6.3	6.1	5.8	6.3
Air Content (%)	7.2	7.5	6.8	6.7
2. Melment L-10 Mixtures				
Cement (lb/yd^3) 1/	648	648	649	656
Water (lb/yd^3) 1/	228	228	229	231
w/c Ratio	0.35	0.35	0.35	0.35
Melment L-10 (% s/c)	0.73	0.59	0.55	0.55
A/E Agent (ml/lb) 3/	14.1	16.4	23.8	26.1
Slump (in.) 4/	5.5	5.8	5.5	5.6
Air Content (%)	7.3	7.3	7.1	6.1

1/ To convert from lb/yd^3 to kg/m^3 multiply by 0.594.
2/ $^oC = 5/9(^oF - 32)$.
3/ To convert from ml/lb to ml/kg multiply by 2.20.
4/ To convert from in. to mm multiply by 25.4.

Table 32

Characteristics of Fresh Concretes

Cement No. 21818

	Temperature - °F 2/			
	45	60	73	90
1. Mighty-150 Mixtures				
Cement (lb/yd^3) 1/	654	659	656	664
Water (lb/yd^3) 1/	229	231	230	232
w/c Ratio	0.35	0.35	0.35	0.35
Mighty-150 (% s/c)	0.40	0.36	0.29	0.34
A/E Agent (ml/lb) 3/	6.1	6.6	7.0	9.0
Slump (in.) 4/	5.8	5.5	6.3	5.8
Air Content (%)	7.6	6.8	7.3	6.2
2. Melment L-10 Mixtures				
Cement (lb/yd^3) 1/	657	659	659	665
Water (lb/yd^3) 1/	230	231	231	233
w/c Ratio	0.35	0.35	0.35	0.35
Melment L-10 (% s/c)	0.56	0.47	0.42	0.42
A/E Agent (ml/lb) 3/	6.6	7.0	7.0	9.0
Slump (in.) 4/	6.0	6.2	6.9	5.8
Air Content (%)	7.1	6.8	6.9	6.0

1/ To convert from lb/yd^3 to kg/m^3 multiply by 0.594.
2/ $^oC = 5/9(^oF - 32)$.
3/ To convert from ml/lb to ml/kg multiply by 2.20.
4/ To convert from in. to mm multiply by 25.4.

cement hydration reactions which, in some manner, modify or decrease the affinity of the cement surface for admixture. If temperature is lowered, those reactions will proceed at a slower rate, thus allowing more active surface to remain which will interact with a larger percentage of admixture.

The slopes of the plots between 45 and 73°F (7 and 23°C) indicate an increase of roughly 0.0061% admixture solids by weight of cement (s/c) per °F (0.011% s/c per °C). In terms of liquid admixture needed per delivery unit of concrete, this translates to 1.2 fl oz/yd^3 (27 ml/m^3) of Mighty-150 and 2.6 fl oz/yd^3 (58 ml/m^3) for every decrease of 1°F (0.55°C) in temperature below 73°F (23°C). This could add to the cost of producing SWR concretes in cooler weather. Above 73°F (23°C), the general trend of decreasing admixture requirement is disrupted. This may reflect some evaporation losses which were unavoidable as the mixer could not be covered during the mix cycle. Furthermore, it is possible that hydration has proceeded so rapidly at this temperature that the admixture is no longer as effective in dispersing the cement

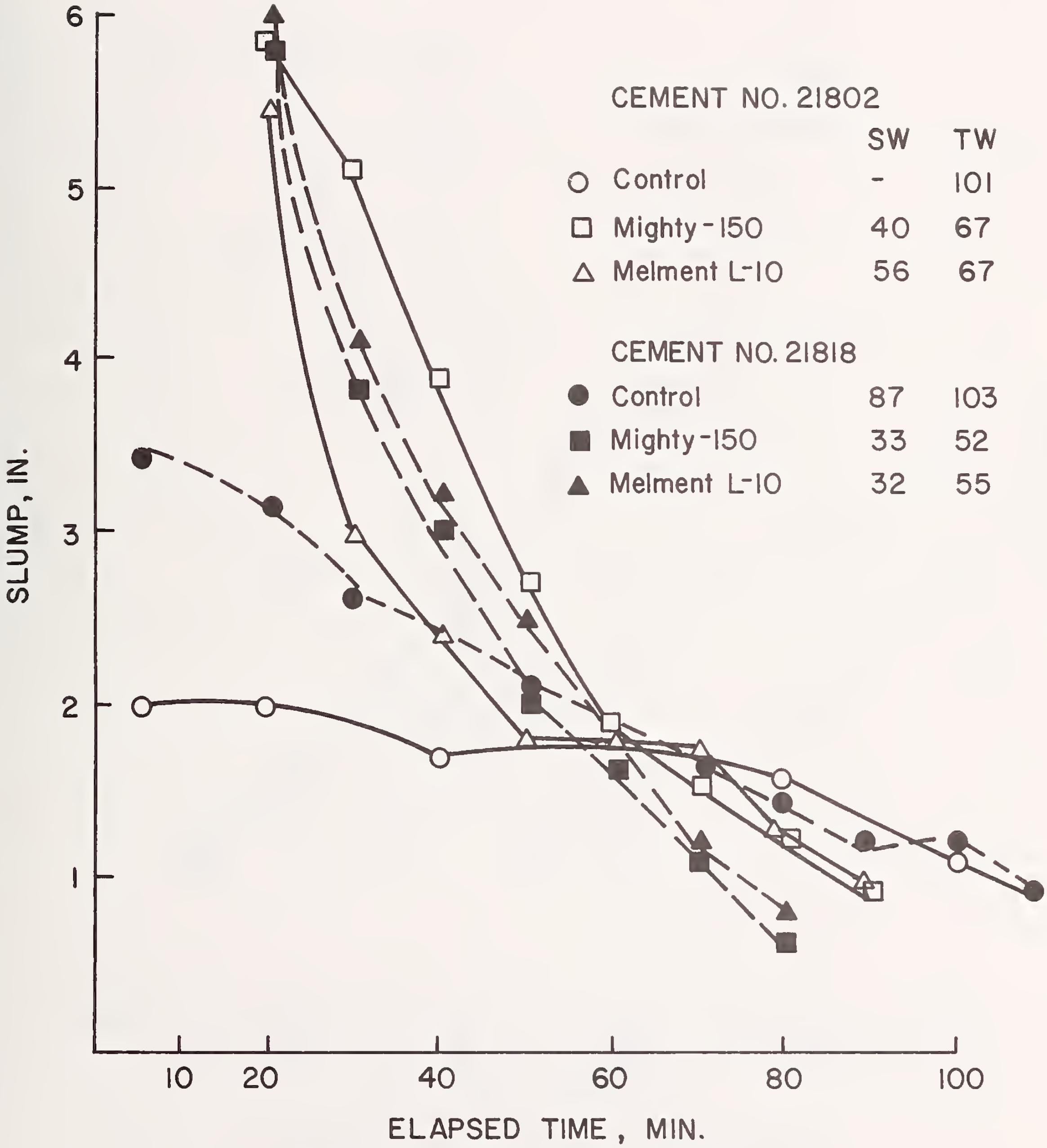

FIGURE 36. SLUMP LOSS AT 45° F

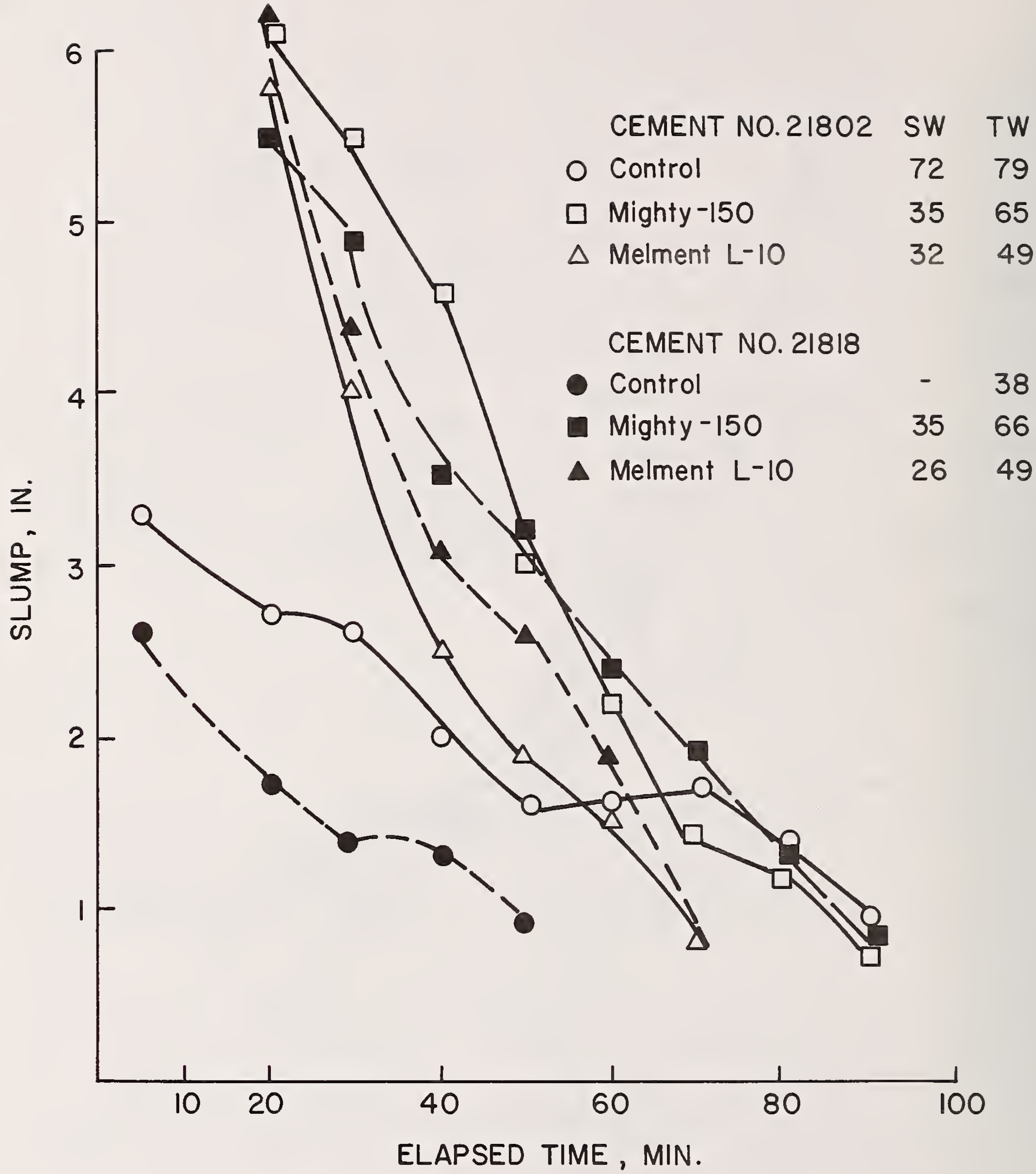

FIGURE 37. SLUMP LOSS AT 60° F

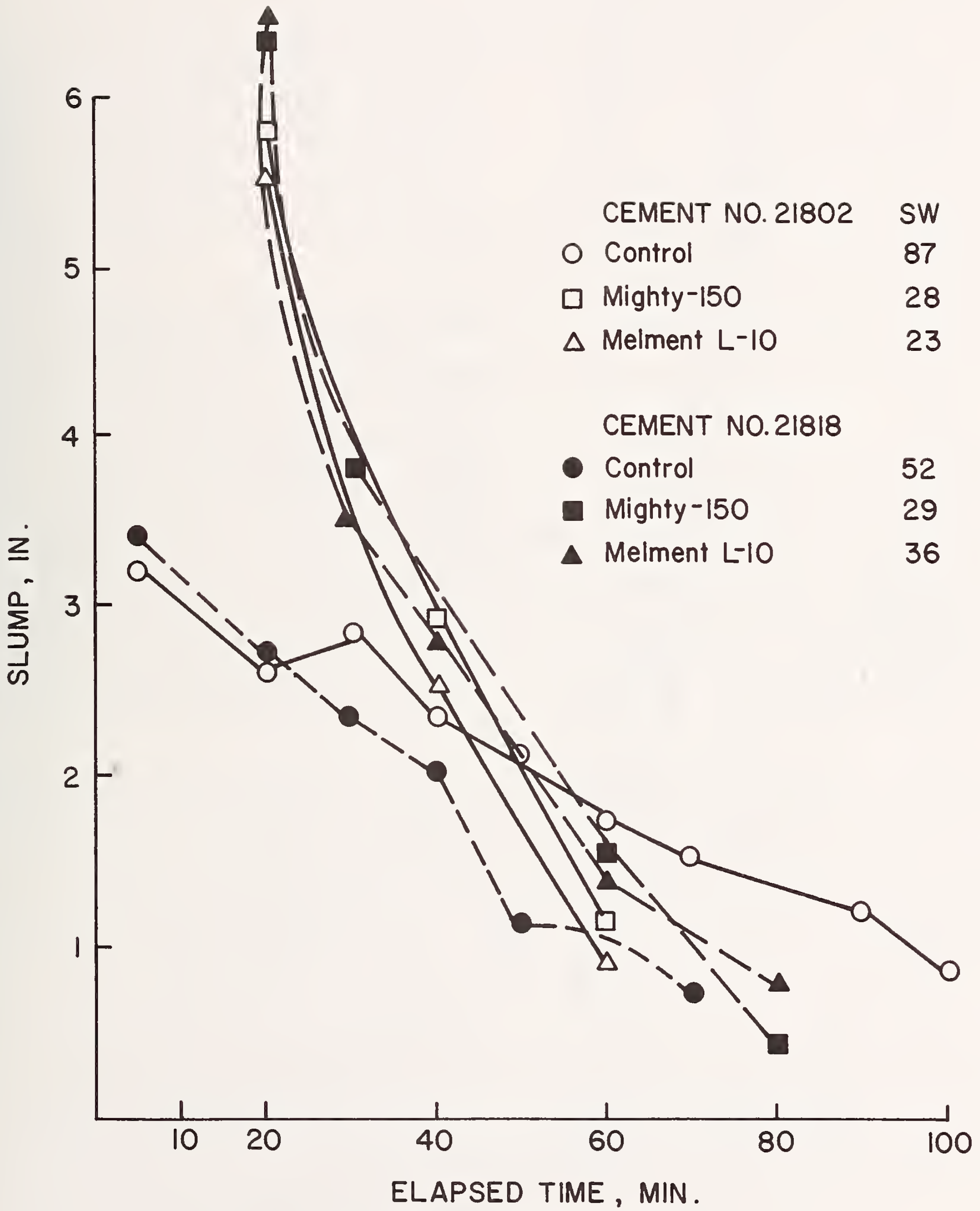

FIGURE 38. SLUMP LOSS AT 73° F

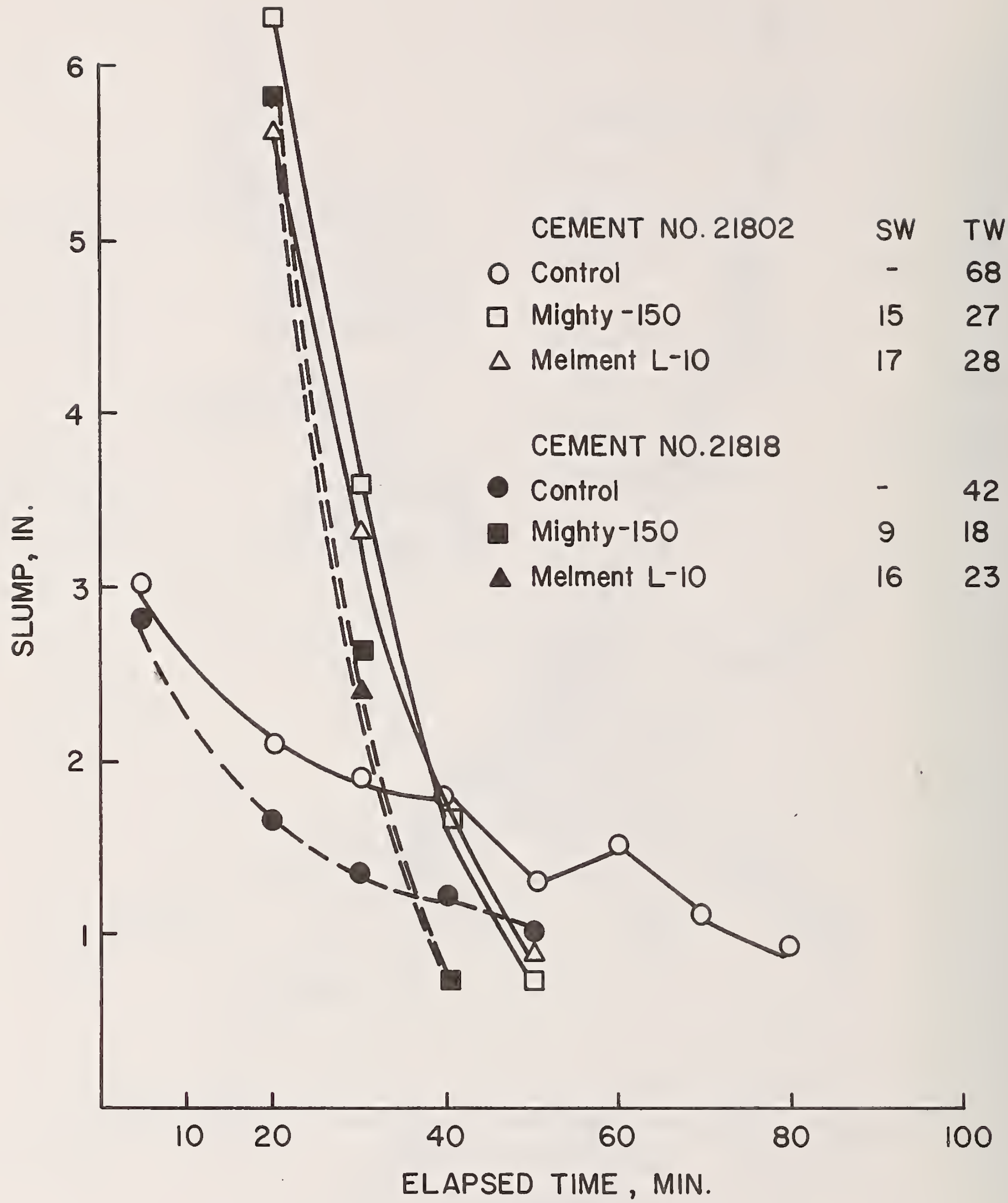

FIGURE 39. SLUMP LOSS AT 90° F

grains, thus offsetting the aforementioned surface effects.

At all temperatures studied, significantly more Melment L-10 (on a solids basis) than Mighty-150 is needed to obtain a given slump. The average dosage difference is approximately 20 percent for cement No. 21802, and 40 percent for cement No. 21818.

When comparing the two cements, comparable differences for dosage requirements can be seen. On the average, cement No. 21802 required approximately 50 percent more Mighty-150, and 30 percent more Melment L-10 than did cement No. 21818. Evidently, admixture demand necessary to obtain a fixed slump and w/c ratio can vary greatly depending on the particular cement being used.

6.3 Slump Loss

Plots of slump versus time after the start of initial mixing are shown in Figs. 36 through 39 for the various temperatures investigated. It is seen that the controls behave in a manner typical of conventional concrete prepared with cements not exhibiting false set or premature stiffening. There is a gradual loss of slump from an initial value of approximately 3 in. (75 mm) to a final value somewhat less than 1 in. (25 mm) over a period ranging from 90-120 minutes at low temperatures to 50-80 minutes at the highest temperature. For the control mixtures, concretes prepared with cement No. 21818 exhibited a greater rate of slump loss at all temperatures than did those prepared with cement No. 21802.

Slump loss characteristics for mixtures containing SWR are dramatically different from those of the controls. A rapid loss of slump, even at relatively low temperatures, is evident. Part of this increased rate of slump loss may be due to the fact that, as noted by Gaynor (14), concretes prepared at higher initial slumps exhibit higher rates of slump loss. It is seen, however, that the rates of loss are so great that, when one takes into account the fact that the SWR curves are displaced 20 minutes along the time axis to allow for the delayed addition, in most cases the total time one has to work with those mixtures is significantly reduced. It is also interesting to note the increased spread between the various combinations of SWR and cements at lower temperatures. These differences become much less noticeable at 73°F (23°C) and 90°F (32°C). There do not appear to be any consistent differences in behavior of the naphthalene versus the melamine based materials with regards to slump loss for both of these cements, although at the lowest temperature studied the mixtures containing Melment L-10 exhibit a higher rate of slump loss in the 6 in. to 3 in. region (152 to 76 mm). Slump loss parameters are plotted versus temperature for concretes prepared with cement No. 21802 in Fig. 40 and for those prepared with cement No. 21818 in Fig. 41. An obvious trend of decreasing SW and TW with increasing temperature is seen. The plots are smoother for cement No. 21802 than for cement No. 21818, the latter exhibiting relative insensitivity to temperature from 45°F (7°C) to 73°F (23°C). For the first cement, No. 21802, total working times range from almost 70 minutes at 45°F (7°C) to about 30 minutes at 90°F (32°C). This repre sents a factor of 2.3, while controls prepared from the same cement lost a factor of only 1.5 over the same temperature range. Slump windows for the same cement show a similar rate of loss over the temperature range studied, showing a ratio of 2.7 for slump windows at 45°F (7°C) as compared to those at 90°F (32°C).

When the two cements are compared using the same SWR, little consistent difference in slump loss parameters can be found. For mixtures containing Mighty-150, total working times and slump windows are nearly identical, except at the lowest temperature, 45°F (7°C), where cement No. 21802 shows higher values. For mixtures containing Melment L-10, the results fluctuate, cement No. 21802 showing higher values at 45°F (7°C) and cement No. 21818 showing higher values at 75°F (23°C).

In general, the results of this study support those found by Mailvaganam (15), who investigated the effects of temperature on "super-plasticized" concretes and found increased slump loss with temperature over the range of 60°F (15°C) to 90°F (32°C). The two studies differ in the fact that in Mailvaganam's work the admixtures were added to a control concrete without reducing the water content, and the dosages were held constant over the entire range of temperatures, thus resulting in different initial slumps at each temperature. In addition, in the present study a relatively long delay time was used, while in the work by Mailvanganam a delay of only 3 minutes was employed.

6.4 Setting Time

Setting times were determined using the Proctor penetration apparatus and technique described in ASTM C403-77. As before (page 52) the sample consisted of mortar prepared separately by exclusion

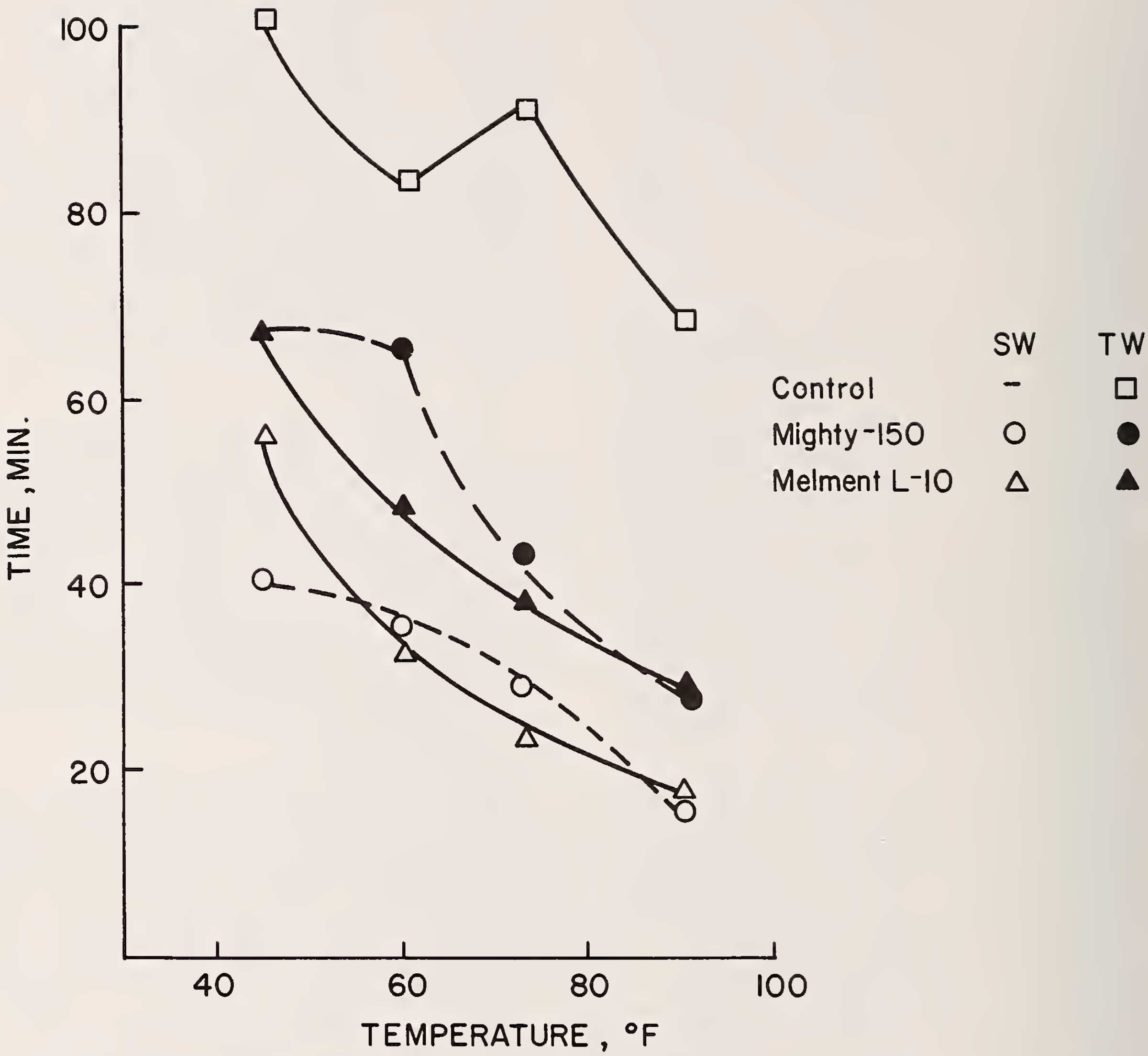

FIGURE 40. SLUMP LOSS PARAMETERS AS A FUNCTION OF TEMPERATURE. CEMENT NO. 21802

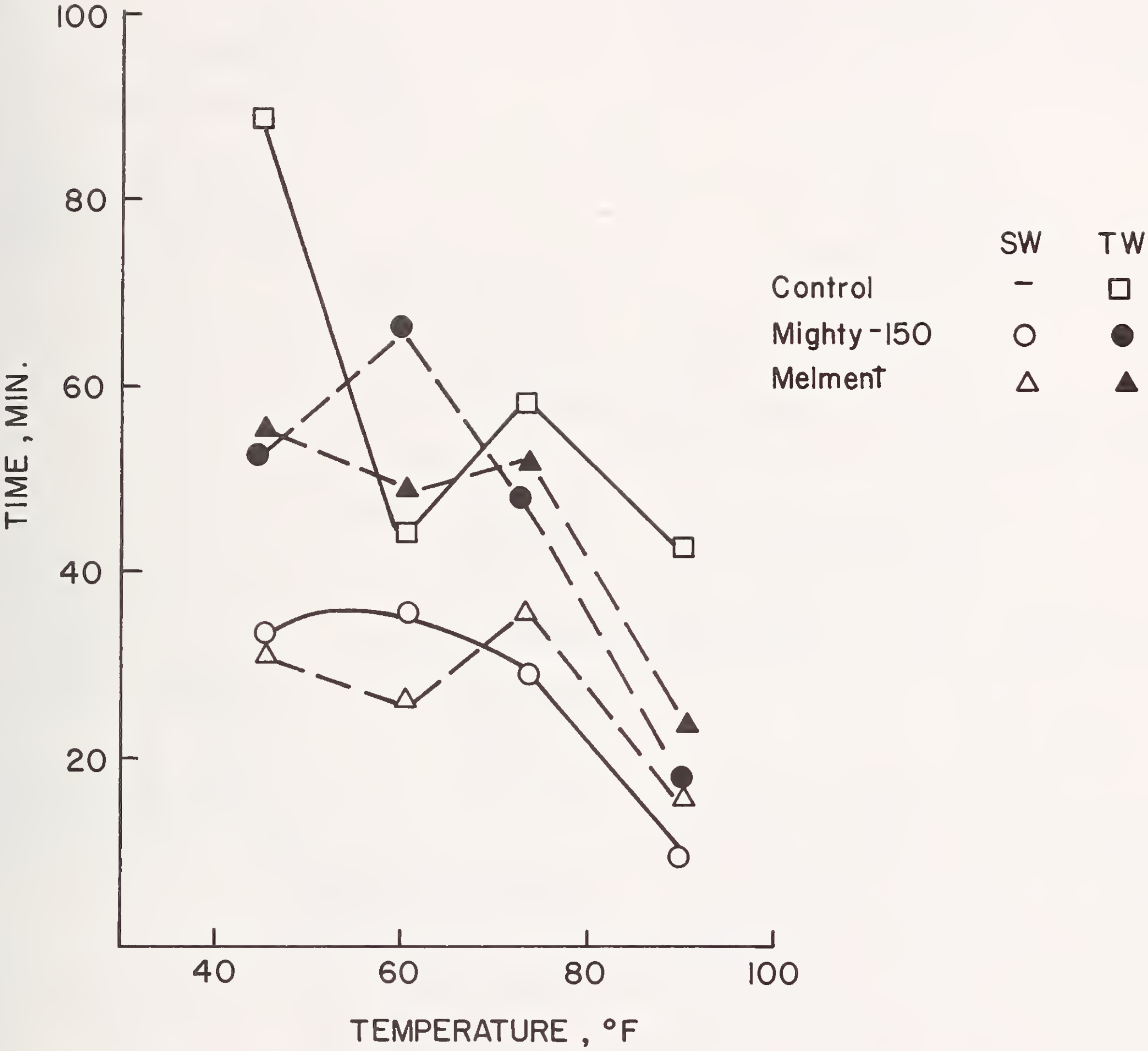

FIGURE 41. SLUMP LOSS PARAMETERS AS A FUNCTION OF TEMPERATURE. CEMENT NO. 21818

of all aggregate greater than that passing the 4.75 mm (No. 4) sieve and its accompanying absorbed water. Results using this type of sample differ somewhat (16) fom those achieved using mortar wet-screened from concrete, however, the results are still valid for bases of comparison between controls and admixtured concretes.

Results for control concrete prepared with the two cements are given in Table 33. As would be expected, setting time increases with a decrease in temperature. The differences in setting characteristics between the two cements are minor.

TABLE 33

Time-of-Set

Control Mixtures

	Initial Set (hr:min)			
	90 °F 1/	73 °F	60 °F	45 °F
Cement No. 21802	3:05	4:00	6:10	9:40
Cement No. 21818	3:00	4:30	6:10	10:35

	Final Set (hr:min)			
	90°F	73°F	60°F	45°F
Cement No. 21802	4:10	5:05	8:45	14:00
Cement No. 21818	4:05	5:45	8:40	14:40

1/ °C = 5/9(°F - 32)

In previous work with these admixtures at the dosage levels needed to obtain a water-cement ratio of 0.35 or less with the present mix design some retardation was found. Results for admixtured concretes, therefore, are presented in Table 34 as retardation times, referenced to the control at the same temperature. Additionally, to overcome the retarding effect which Mighty-150 had on one of the cements at ambient temperature, 0.5% by weight of cement of calcium nitrate was added to the mix at temperatures of 45°F (7°C), 60°F (16°C), and 73°F (23°C). Retardation shows a general increase with decreasing temperature for cement No. 21818, but results are more scattered for cement No. 21802. When admixtures are compared with the same cement at a given temperature, Melment L-10 shows less retardation than Mighty-150. When the two cements are compared with a single water reducer (Melment L-10) at various temperatures an interesting reversal in relative retardation can be seen. At the two highest temperatures of 90 and 73°F (32 and 23°C) cement No. 21802 shows greater retardation then cement No. 21818, at 60°F (16°C) retardations are essentially equal, and at 45°F (7°C) cement No. 21818 shows greater retardation with Melment L-10 then does cement No. 21802. The addition of 0.5% calcium nitrate improves the performance of Mighty-150 in this respect, and has more of an effect on

TABLE 34

Set Retardation

Effect of Temperature

	Retardation of Initial Set (hr:min)			
	90°F	73°F	60°F	45°F 1/
Cement No. 21802				
Mighty-150	1:15	1:40	--	--
Mighty-150 +0.5% $Ca(NO_3)_2$	--	0:30	0:30	+0:20 2/
Melment L-10	1:00	0.55	1:05	0:10
Cement No. 21818				
Mighty-150	0:45	0:30	1:40	3:50
Mighty-150 +0.5% $Ca(NO_3)_2$	--	0:20	1:00	--
Melment L-10	0:15	0:10	0:55	1:55

	Retardation of Final Set (hr:min)			
	90°F	73°F	60°F	45°F
Cement No. 21802				
Mighty-150	1:15	2:35	--	--
Mighty-150 +0.5% $Ca(NO_3)_2$	--	1:00	0:25	1:20
Melment L-10	0:50	0:40	0:35	+0:10
Cement No. 21818				
Mighty-150	0:40	1:05	1:50	3:00
Mighty-150 +0.5% $Ca(NO_3)_2$	--	1:00	0:40	--
Melment L-10	0:20	0:20	0:45	1:45

1/ °C = 5/9(°F - 32)
2/ + signifies set acceleration.

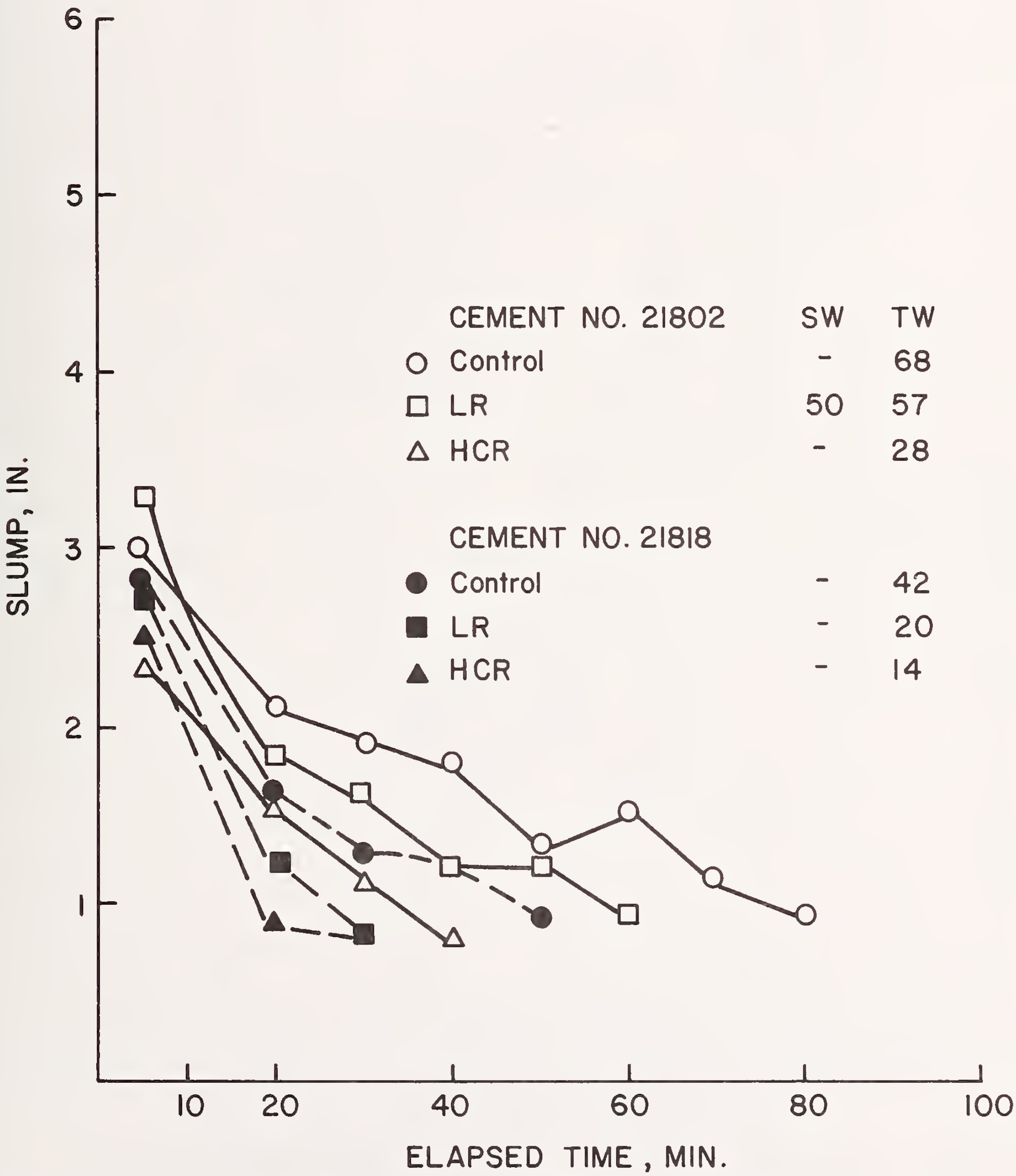

FIGURE 42. SLUMP LOSS AT 90° F CONTROLS PLUS CONVENTIONAL WATER REDUCERS

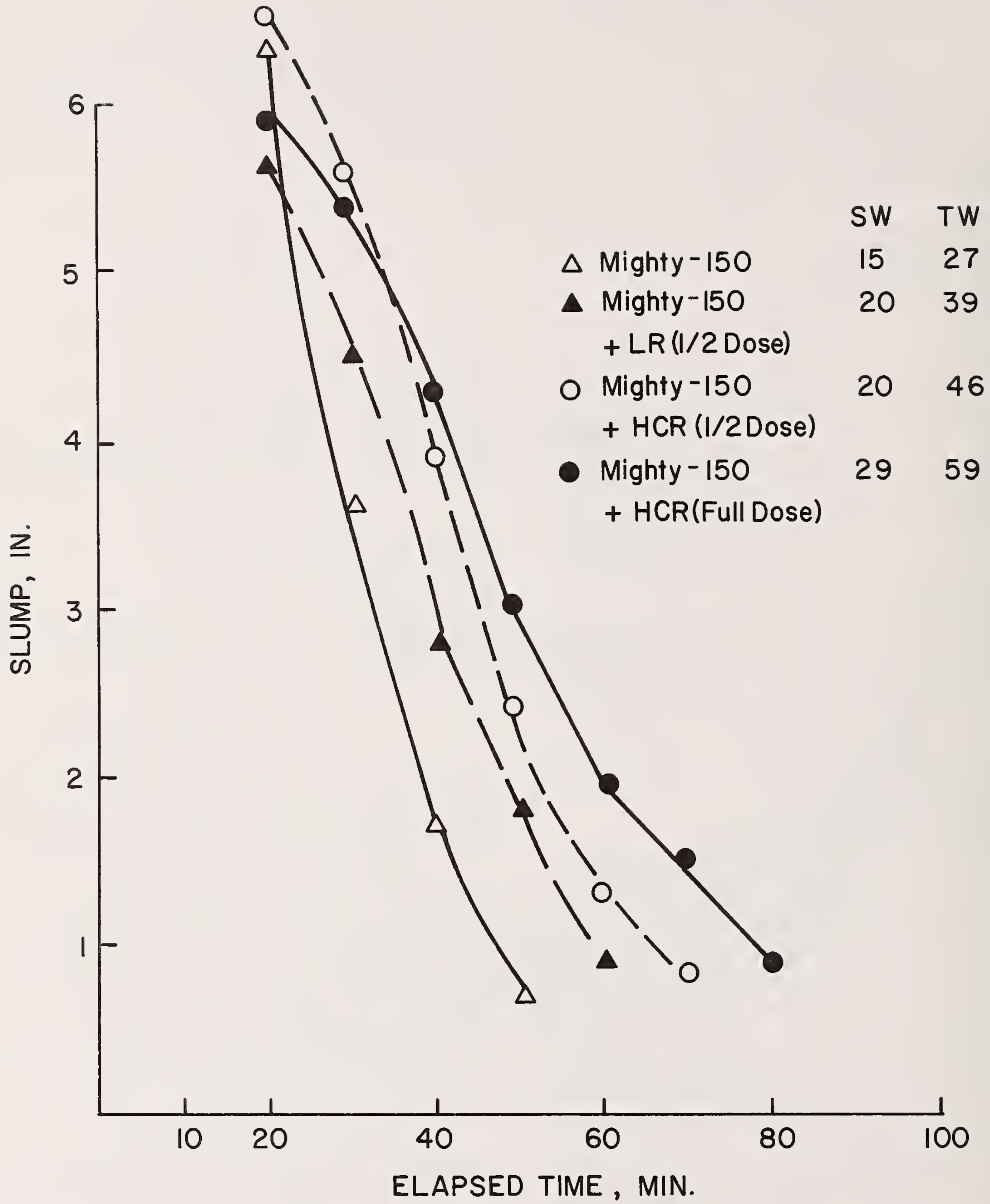

FIGURE 43. SLUMP LOSS AT 90°F. MIGHTY-150 PLUS CONVENTIONAL WATER REDUCERS. CEMENT NO. 21802

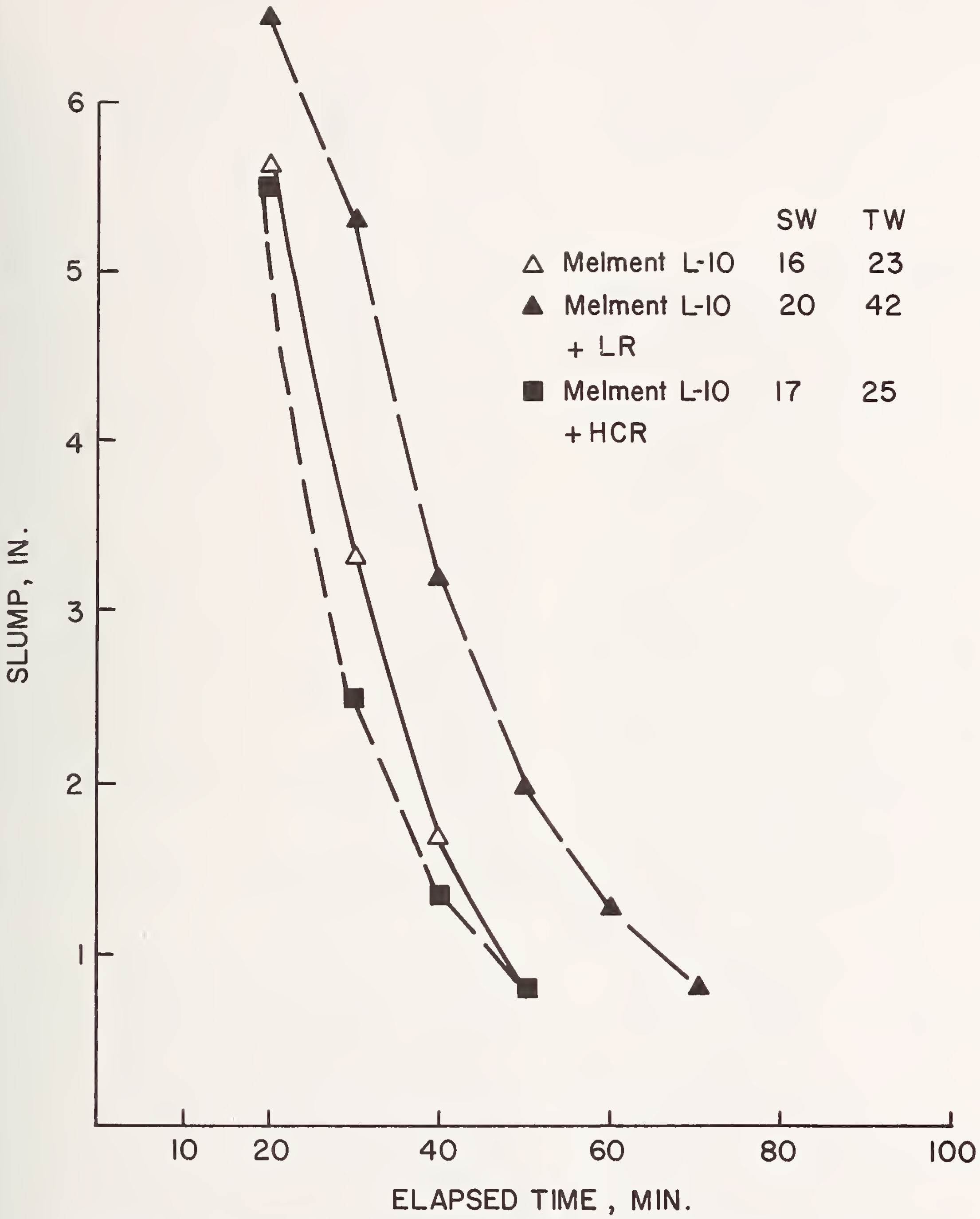

FIGURE 44. SLUMP LOSS AT 90°F. MELMENT L 10 PLUS CONVENTIONAL WATER REDUCERS. CEMENT NO. 21802

those mixtures prepared from cement No. 21802. With cement No. 21818, the accelerator appears more effective at 60°F (16°C) than at 73°F (23°C).

Finally, it can be said that the set retardations brought about by these admixtures, though experimentally significant, are not excessive and pose no serious practical problems over the range of temperatures covered by this study. The use of either chemical accelerators, or other expedients such as heated water or aggregates should enable users to avoid any serious problems with setting times.

6.5 Use of Retarders at Elevated Temperatures

In a recent publication, Hester (17) has discussed the use of retarders in combating slump loss experienced when using SWR at relatively high temperatures. Additionally, the mini-slump series has suggested that various retarders may function as low cost, partial replacements for SWR in concrete mixes. For the present study lignosulfonate-based (LR) and hydroxycarboxylic acid-type retarders (HCR) were added to control concretes at the midrange of the manufacturer's recommended dose. This dosage was then reduced by 50 percent (except for one instance) and the retarders added to mixtures containing SWR. The dosage of SWR was adjusted to obtain an initial slump equal to that of the retarder-free mixture. Dosage requirements are given in Table 35 for cement No. 21802 and Table 36 for cement No. 21818. It is seen that partial replacement of SWR by an equivalent weight of retarder leads to significant reduction in SWR dosage while maintaining constant initial slump.

Slump loss for control concretes, with and without retarders, is shown in Fig. 42. It is seen that the addition of retarders increased the rate of slump loss for both cements. This effect has been seen by other workers (18), and was discussed at a recent ACI symposium (19). Conversely, when retarders are added to concretes containing Mighty-150, beneficial effects on slump loss are evident (Fig. 43). The rate of slump loss is reduced by replacement of part of the Mighty-150 with conventional retarders, the HCR-based retarder appearing to be much more effective in this respect, as its dosage was only about 1/3 that of the LR-based admixture, yet its effect in reduction of slump loss was greater. The benefits in addition of retarder are not proportional to its dosage, as the difference between full and half-dose curves for HCR is less than the difference betwee half-dose HCR and control (no retarder). For the Melment L-10, HCR has little effect on slump loss. In this case (cement No. 21802 - Fig. 44) LR admixture is more effective. For the second cement (cement No. 21818 - Figs. 45 and 46), the opposite behavior is seen. Here the two retarders are about equally effective in reducing slump loss in Mighty-150 concrete, but the HCR is more effective in concrete made with Melment L-10. Thus, there seems to be a complex interaction between cement composition, SWR type, and retarder type which cannot be separated out based on the relatively small number of tests conducted in the present investigation.

TABLE 35

Admixture Dosage

Cement No. 21802

at 90°F 1/

SWR (Dose - % s/c)	Retarder (Dose - % s/c)	Reduction in SWR	Slump (in.) 2/	Air (%)
Mighty-150 (0.41%)	None	--	6.3	6.7
Mighty-150 (0.30%)	LR (0.11%)	27%	5.6	7.1
Mighty-150 (0.37%)	HCR (0.04%)	10%	6.5	7.9
Mighty-150 (0.37%)	HCR (0.08%)	10%	5.9	8.5
Melment L-10 (0.55%)	None	--	5.6	6.1
Melment L-10 (0.44%)	LR (0.11%)	20%	6.5	7.6
Melment L-10 (0.51%)	HCR (0.04%)	7%	5.5	6.2

1/ °C = 5/9(°F - 32)
2/ To convert from in. to mm multiply by 25.4.

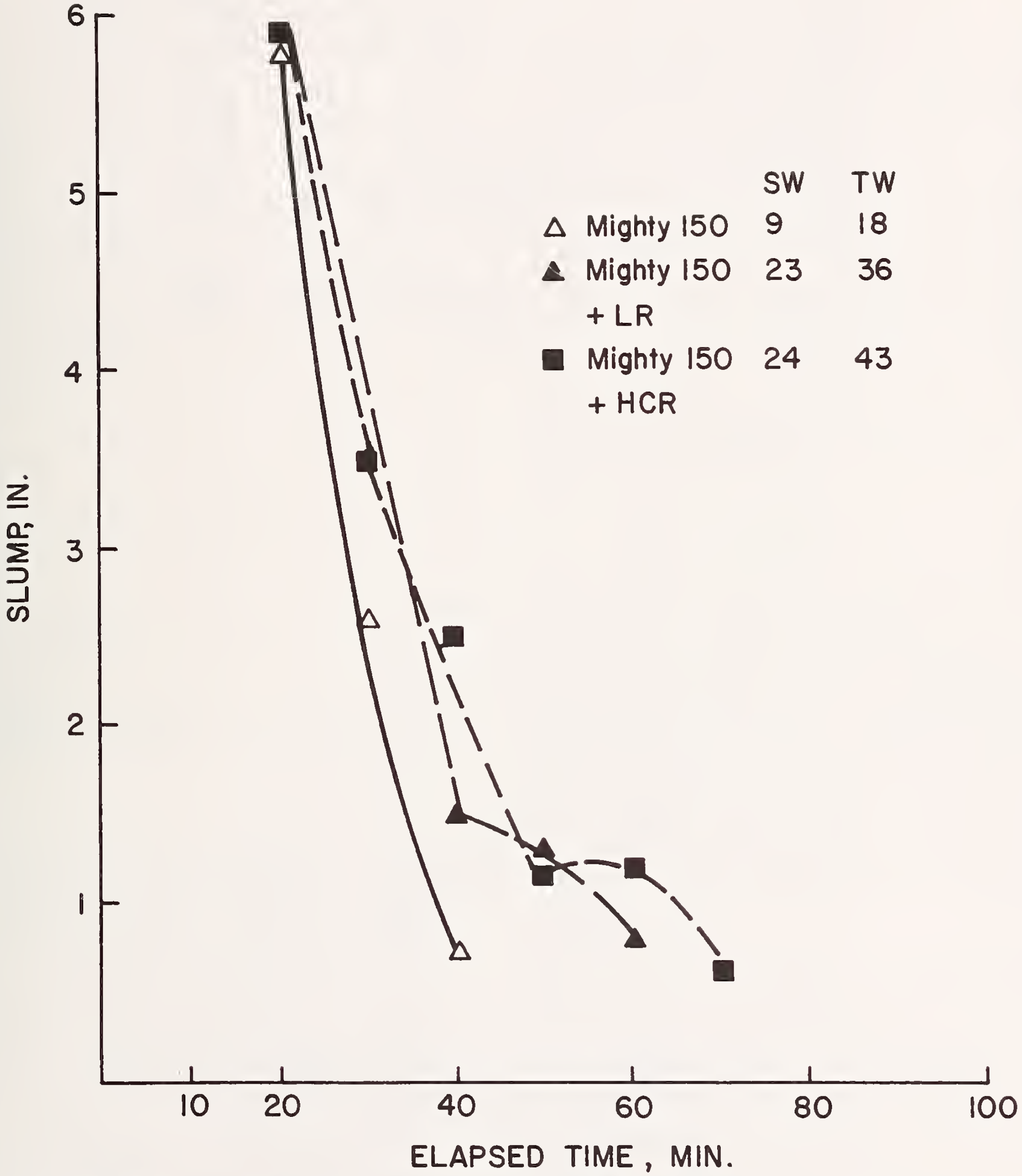

FIGURE 45. SLUMP LOSS AT 90°F. MIGHTY-150 PLUS CONVENTIONAL WATER REDUCERS. CEMENT NO. 21818

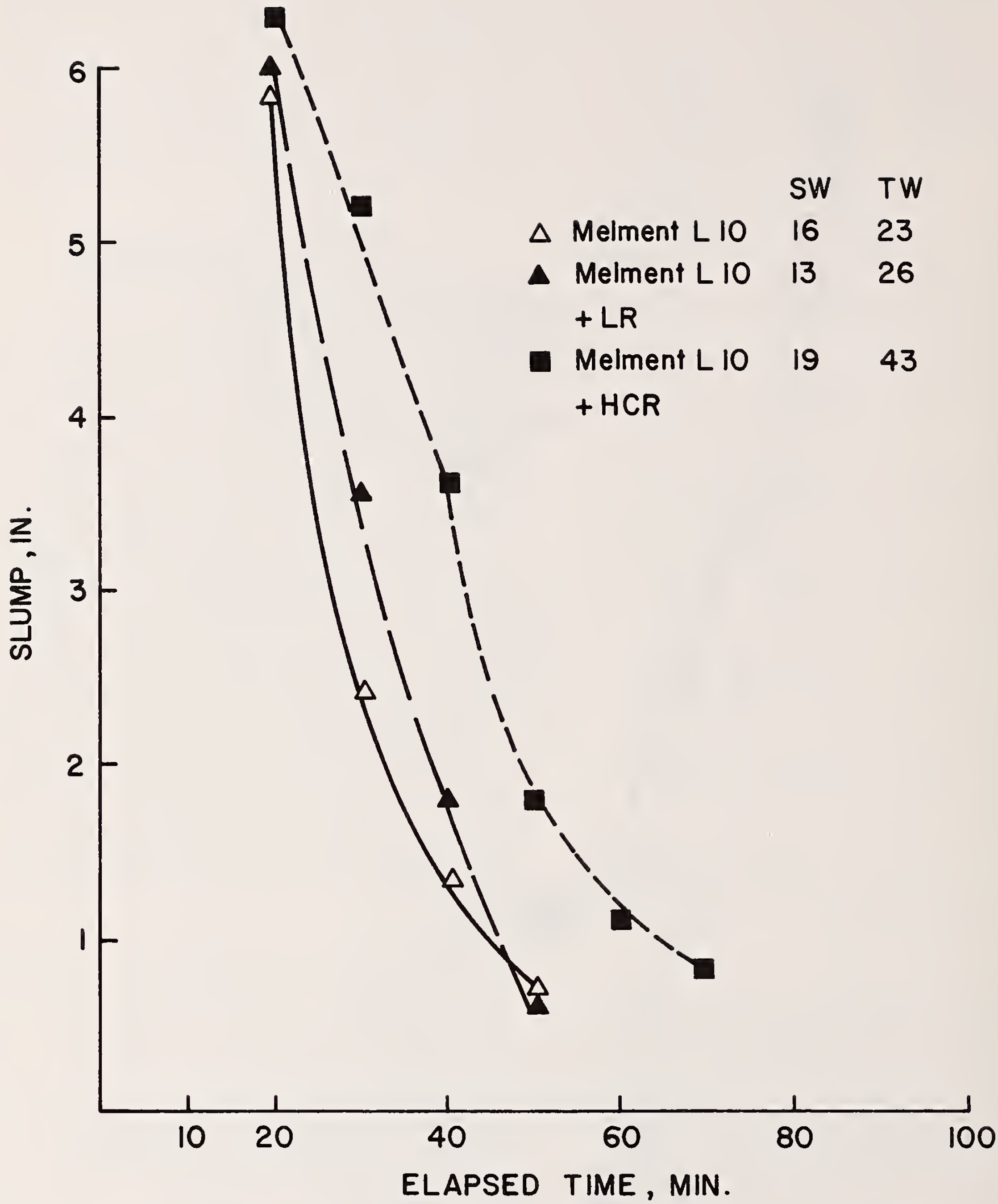

FIGURE 46. SLUMP LOSS AT 90°F. MELMENT L 10 PLUS CONVENTIONAL WATER REDUCERS. CEMENT NO. 21818

TABLE 36

Admixture Dosage

Cement No. 21818

at 90°F 1/

SWR (Dose - % s/c)	Retarder (Dose - % s/c)	Reduction in SWR	Slump (in.) 2/	Air (%)
Mighty-150 (0.34%)	None	--	5.8	6.2
Mighty-150 (0.25%)	LR (0.11%)	26%	5.9	6.9
Mighty-150 (0.30%)	HCR (0.04%)	13%	5.9	6.0
Melment L-10 (0.42%)	None	--	5.8	6.0
Melment L-10 (0.34%)	LR (0.11%)	19%	6.0	6.7
Melment L-10 (0.41%)	HCR (0.04%)	2%	6.3	6.9

1/ $^{\circ}C = 5/9(^{\circ}F - 32)$
2/ To convert from in. to mm multiply by 25.4.

In previous tests (see Section 4.4), serious retardation effects when conventional retarders were used as SWR partial replacements at ambient laboratory temperatures were noted. Data from the present study (Table 37) indicate that although significant retardation is seen for combinations of retarders and SWR (Mixes 6-10), in only one case (Mix 8) is retardation to be considered excessive. In this case the full dose of HCR was used, while in all other cases 1/2 dose was employed. A comparison of retardation times for combination mixtures (5-9) with the sum of the retardations for SWR and retarder mixtures indicates a synergistic effect. That is, although the SWR dosage in the combination mixture is reduced up to 20 percent, and the retarder dosage is reduced 50 percent, the retardation is significantly greater than that which would be expected from simple summation of the retardations in those concretes where the admixtures are kept separate. In all cases, retardations in those mixtures containing HCR are greater than those found in mixtures containing LR. Similar results are seen for cement No. 21818 (Table 38), although for this cement retardations are somewhat less, most probably due to the lower dosages of SWR required to obtain equal slump.

7. Field Trials

Although the bulk of this project was devoted to laboratory evaluations, a limited amount of field work was completed. The objective was not to participate in actual field construction jobs, but to prepare typical concrete mixtures under field conditions using full-scale mixing equipment. Based on previous laboratory work, the two most promising areas for application of SWR appeared to be in overlay mixtures and in high-strength mixtures for cast-in-place bridge decks. To evaluate the performance of SWR in mixtures used in these applications arrangements were made for the use of a mobile concrete mixer ("Concrete Mobile") and for the use of a ready-mix truck at a local concrete yard.

7.1 Overlay Mixtures ("Concrete Mobile")

The Concrete-Mobile® 1/ (Figure 47A) is a combination materials transporter and mobile concrete mixing plant. Good success has been achieved in applications where conventional (i.e. low-slump) "Iowa" mixtures have been placed as bridge deck overlays. These mixer/transporters are available as standard models in capacities up to 10 yd^3 (7.6 m^3). Cement, sand, and coarse aggregate are carried in separate bins. Water is carried in a tank located in front of the unit, admixtures are carried in smaller tanks on the side of the unit (Figure 47B).

The concrete mixture is designed on a volume basis (ASTM C685-74). 2/ Sand and coarse aggregates volumes are computed based on pre-determined dry rodded unit weight measurements. The unit is pre-calibrated so that known volumes of cement, sand, and coarse aggregate are delivered per unit time. The water and admixture tanks are equipped with flowmeters and valves so that known volumes of these ingredients can also be delivered in unit time. All solid ingredients drop from the bins onto a main conveyor belt under the action of bin vibrators.

1/ ® IRA Daffin Associates, Lancaster, PA.

2/ ASTM C685-74 "Standard Specification for Concrete Made by Volumetric Batching and Continuous Mixing."

TABLE 37

Setting Time

Cement No. 21802

at 90°F[1/]

No.	SWR (Dose - % s/c)	Retarder (Dose - % s/c)	Time-of-Set (hr:min) Initial	Time-of-Set (hr:min) Final	Retardation (hr:min) Initial	Retardation (hr:min) Final
1	-	--	3:05	4:10	--	--
2	Mighty-150 (0.41%)	--	4:20	5:25	1:15	1:15
3	Melment L-10 (0.55%)	--	4:05	5:00	1:00	0:50
4	-	LR (0.23%)	4:40	5:30	1:35	1:20
5	-	HCR (0.08%)	5:00	6:10	2:05	2:00
6	Mighty-150 (0.30%)	LR (0.11%)	6:50	8:00	3:45	3:50
7	Mighty-150 (0.37%)	HCR (0.04%)	8:50	10:40	5:45	6:30
8	Mighty-150 (0.37%)	HCR (0.08%)	24 hr	31 hr	21 hr	27 hr
9	Melment L-10 (0.44%)	LR (0.11%)	5:40	6:55	2:35	2:45
10	Melment L-10 (0.51%)	HCR (0.04%)	8:00	9:25	4:55	5:15

1/ °C = 5/9(°F - 32)

TABLE 38

Setting Time

Cement No. 21818

at 90°F[1/]

No.	SWR (Dose - % s/c)	Retarder (Dose - % s/c)	Time-of-Set (hr:min) Initial	Time-of-Set (hr:min) Final	Retardation (hr:min) Initial	Retardation (hr:min) Final
1	-	--	3:00	4:05	--	--
2	Mighty-150 (0.34%)	--	3:45	4:45	0:45	0:40
3	Melment L-10 (0.42%)	--	3:15	4:25	0:15	0:20
4	-	LR (0.23%)	4:55	6:10	1:55	2:05
5	-	HCR (0.08%)	4:50	6:10	1:50	2:05
6	Mighty-150 (0.25%)	LR (0.11%)	6:10	7:25	3:10	3:20
7	Mighty-150 (0.30%)	HCR (0.04%)	7:25	9:00	4:25	4:55
8	Melment L-10 (0.34%)	LR (0.11%)	5:25	6:25	2:25	2:20
9	Melment L-10 (0.41%)	HCR (0.04%)	6:40	7:50	3:40	3:45

1/ °C = 5/9(°F - 32)

FIGURE 47A. CONCRETE MOBILE

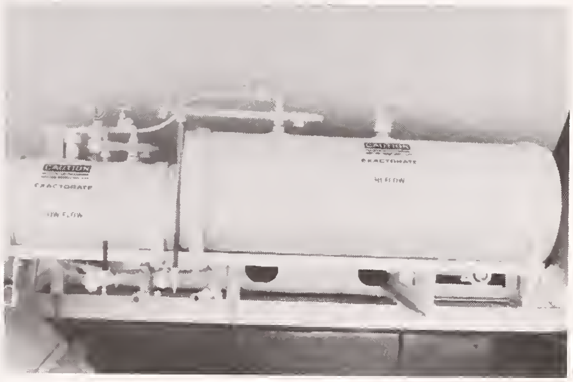

FIGURE 47B. ADMIXTURE TANKS

FIGURE 47C. CONCRETE BEING DISCHARGED FROM AUGER/CHUTE

FIGURE 47. CONCRETE MOBILE OPERATIONS

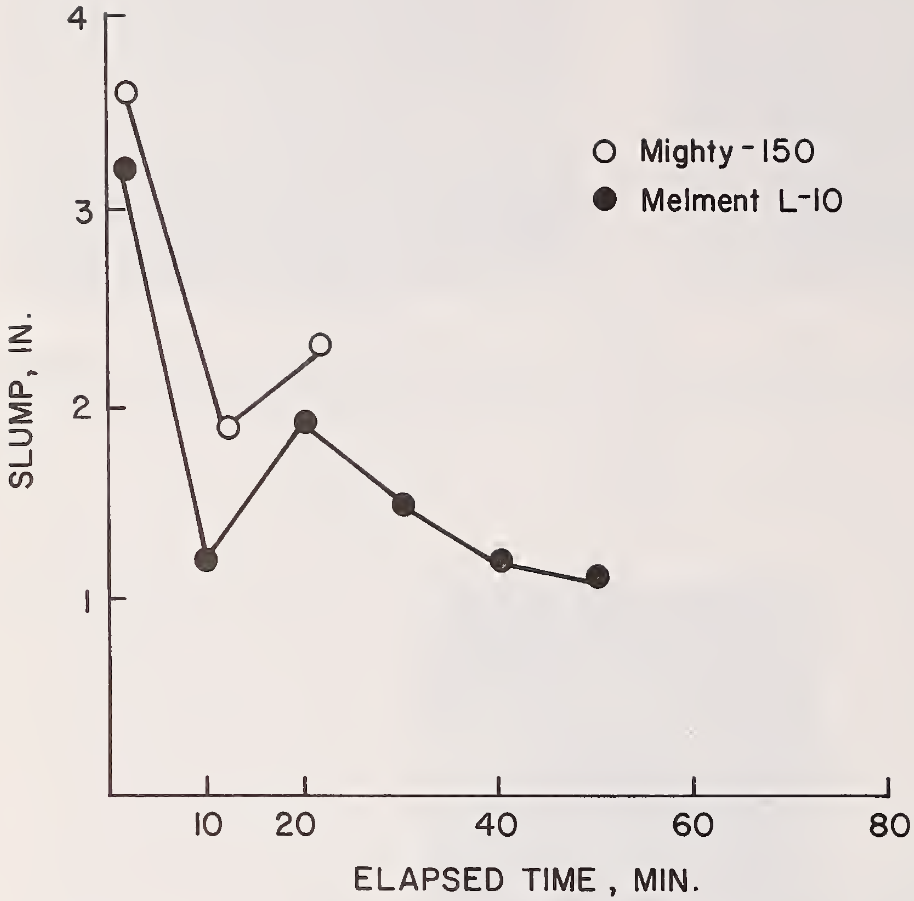

FIGURE 48. SLUMP LOSS IN CONCRETES PRODUCED USING CONCRETE MOBILE

At the charging end of the mix conveyor (at the rear of the unit) the metered flow of water and admixture enters the mixer along with the solid ingredients. The combined auger/paddle mixer homogenizes the concete within a period of about 20 seconds. The mix is then transported through the auger-chute to the desired placement location (Figure 47C).

Full details on construction calibration, and operation of the Concrete-Mobile^R can be found in the user's handbook supplied by the manufacturer with each unit. Only those aspects pertinent to the current project will be described in this report.

7.1.1 Materials and Mixing Procedures

Type II cement was received in 55 gal (208 L) drums, blended, and stored in 30 gal (114 L) water-tight barrels. Chemical analysis is shown in Appendix D (Lot No. 21813). Sand and gravel were purchased from a local supplier, properties are given in Table 39.

Conrete Mobile^R obtained on loan from the manufacturer. The cement meter/feeder, sand and gravel dials, and water meters were all calibrated using the job materials prior to actual concrete production.

Mix proportions for control, Mighty-150, and Melment mixtures are shown in Table 40. The dosage rate for Melment L-10 in this particular mixture is anomalously low, and could reflect an error in dilution or flowmeter reading. As cement supplies were exhausted, replicate batches could not be made so this question, unfortunately, was left unresolved. A/E agent dosages were much greater for the mixtures containing SWR then for the control mixture.

Properties of the fresh concretes obtained from the unit are shown in Table 41. All samples were taken after allowing the auger-chute to discharge for an initial period of 30 seconds.

TABLE 39

Aggregate Properties

Concrete-Mobile^R Mixtures

	Specific Gravity	Absorption (%)	Moisture Content (%)	Dry Rodded Unit Weight (lb/ft^3)1/
Sand	2.68	2.0	5.0	110
Gravel (0.75-in. top size)2/	2.70	1.8	1.8	101

1/ To convert from lb/ft^3 to kg/m^3 multiply by 16.038.
2/ To convert from in. to mm multiply by 25.4

Admixtures were purchased in drums from the manufacturers, and stored in our laboratories until ready for use. It was necessary to dilute the admixture just prior to use in order to obtain the necessary sensitivity on the admixture flowmeters. The air-entraining agent (Darex^R 1/) was diluted 1:5, Mighty-150 was diluted 1:15, Melment L-10 was diluted 1:19.

The unit used for production of the concrete was a Model 8CM chassis mounted

1/ ^{R}Registered Trademark, W. R. Grace and Company, Cambridge, MA.

7.1.2 Slump Loss and Compressive Strength

Slump loss was determined at 10 minute intervals on the mixtures prepared with Mighty-150 and Melment. Slump loss was not determined on the control mixture due to its low initial slump. Results are present in Figure 48. Mixtures show good slump retention, although data for Mighty-150 mixtures are incomplete after 20 minutes. This behavior is similar to that seen in the laboratory tests on slump loss in overlay mixtures (see Section 5.3). As in practice, the concrete would be produced just prior to placement, these long working times indicated that slump loss would not be a problem

TABLE 40

Mix Properties - Concrete Mobile[R] Mixtures

No.	SWR	Dosage (% s/c)	A/E Agent (ml/lb) 2/	Quantities lb/yd^3-SSD 1/ Water	Cement	Sand	Gravel	% Sand Abs. Vol.
1	None	-	0.8	258	791	1,392	1,477	48.8
2	Mighty-150	0.14	4.2	272	777	1,367	1,450	48.7
3	Melment L-10	0.04 3/	3.8	267	781	1,375	1,459	48.7

1/ To convert from lb/yd^3 to kg/m^3 multiply by 0.594.
2/ To convert from ml/lb to ml/kg multiply by 2.20.
3/ Questionable value.

TABLE 41

Properties of Fresh Concrete

Concrete-Mobile[R] Mixes

No.	SWR	Slump (in.) 1/	Air Content (%)	Unit Weight (lb/ft^3) 2/	Temperature (°F) 3/
1	None	0.7	6.4	145	73
2	Mighty-150	3.6	7.0	143	73
3	Melment L-10	3.2	6.8	144	68

1/ To convert from in. to mm multiply by 25.4.
2/ To convert from lb/ft^3 to kg/m^3 multiply by 16.038.
3/ $^oC = 5/9(^oF - 32)$

in use of SWR in this type of operation. Specimens for determination of compressive strength were prepared at the placement site and stored outside overnight. They were then transferred to a moist room held at 73°F (23°C) and duplicate specimens were tested at 1 day, 3 days, 7 days, and 28 days. Results are shown in Table 42.

The low 1-day strength of the Melment L-10 specimen can be attributed to a drop in temperature to 45°F (7°C) during the first night of storage. The low strength of the Mighty-150 specimen can be attributed to the higher air content as compared to that of the control (see next section).

TABLE 42

Compressive Strength of Overlay (Concrete-Mobile[R] Concretes)

No.	SWR	Compressive Strength (psi) 1/ 1 Day	3 Days	7 Days	28 Days
1	None	1,670	3,000	4,490	6,080
2	Mighty-150	1,200	3,150	3,810	5,200
3	Melment L-10	600	2,500	3,900	5,620

1/ To convert psi to MPa multiply by 6.896×10^{-3}.

7.1.3 Air Content and Durability Testing

Hardened air content and air-void parameters were determined on 3x3x11-1/4-in. (76x76x286 mm) prisms cast from each mixture. Linear traverse techniques (ASTM C457-71) were employed. Results are shown in Table 43. In all cases, air-void parameters meet the criteria established by ACI (20) for bridge deck construction.

Triplicate specimens were cast from each batch for determination of freeze-thaw durability (ASTM C666-77: Procedure A), and deicer scaling resistance (ASTM C672-76). Results after 300 cycles of test are presented in Table 44. A value of 80 was chosen as the specified minimum value of Relative Dynamic Modulus for discontinuing the rapid freeze-thaw testing. Results for control specimens indicated good durability. Results for Mighty-150 and Melment L-10, however, were conflicting. Average durability factor for the Mighty-150 specimens was 84, yet only very slight scaling was evidenced in the deicer slabs. Durability factor for the Melment L-10 mix was excellent, yet moderate to severe scaling was noted in the deicer slabs. Some of the scatter in the Mighty-150 data could be reduced by elimination of the third specimen, which exhibited much lower DF than the other two. All Melment specimens, however, did exhibit moderate to severe scaling, thus indicating a real deterioration in this case.

7.2 Ready-Mix Operations

The objective of this task was to prepare concrete mixtures at a local ready-mix yard using typical mixing equipment. The fresh concrete was tested for slump, air content, and setting time. Specimens were prepared for strength, durability, and linear traverse analysis. Super-water reducers were added in the delayed addition mode in order to simulate field addition of admixture.

TABLE 43

Air Contents and Air-Void Parameters

Overlay (Concrete-Mobile^R) Concretes

No.	SWR	Air Content (%)	Voids per inch 1/	Specific Surface (in.^{2}/in.^{3}) 2/	Void Spacing Factor (in.) 3/
1	None	5.2	12.9	999	0.0050
2	Mighty-150	6.6	16.2	983	0.0046
3	Melment L-10	5.3	14.9	1,131	0.0044

1/ To convert from voids per inch to voids per mm multiply by 0.0394.

2/ To convert from in.^{2}/in.^{3} to mm^2/mm^3 multiply by 0.0394.

3/ To convert from in. to mm multiply by 25.4.

TABLE 44

Freeze-Thaw Durability and Deicer Scaling Resistance

Overlay (Concrete-Mobile^R) Concretes

No.	SWR	ASTM C666-77: Procedure A — Expansion (%)	ASTM C666-77: Procedure A — Durability Factor 1/ Average	ASTM C666-77: Procedure A — Durability Factor 1/ Individual	ASTM C672-76 Scale Rating 2/
1	None	0.026	94	(95-94-92)	1
2	Mighty-150	0.046	84	(96-86-69)	1
3	Melment L-10	0.027	95	(98-96-92)	4

1/ See ASTM C666-76
2/ See ASTM C672-76

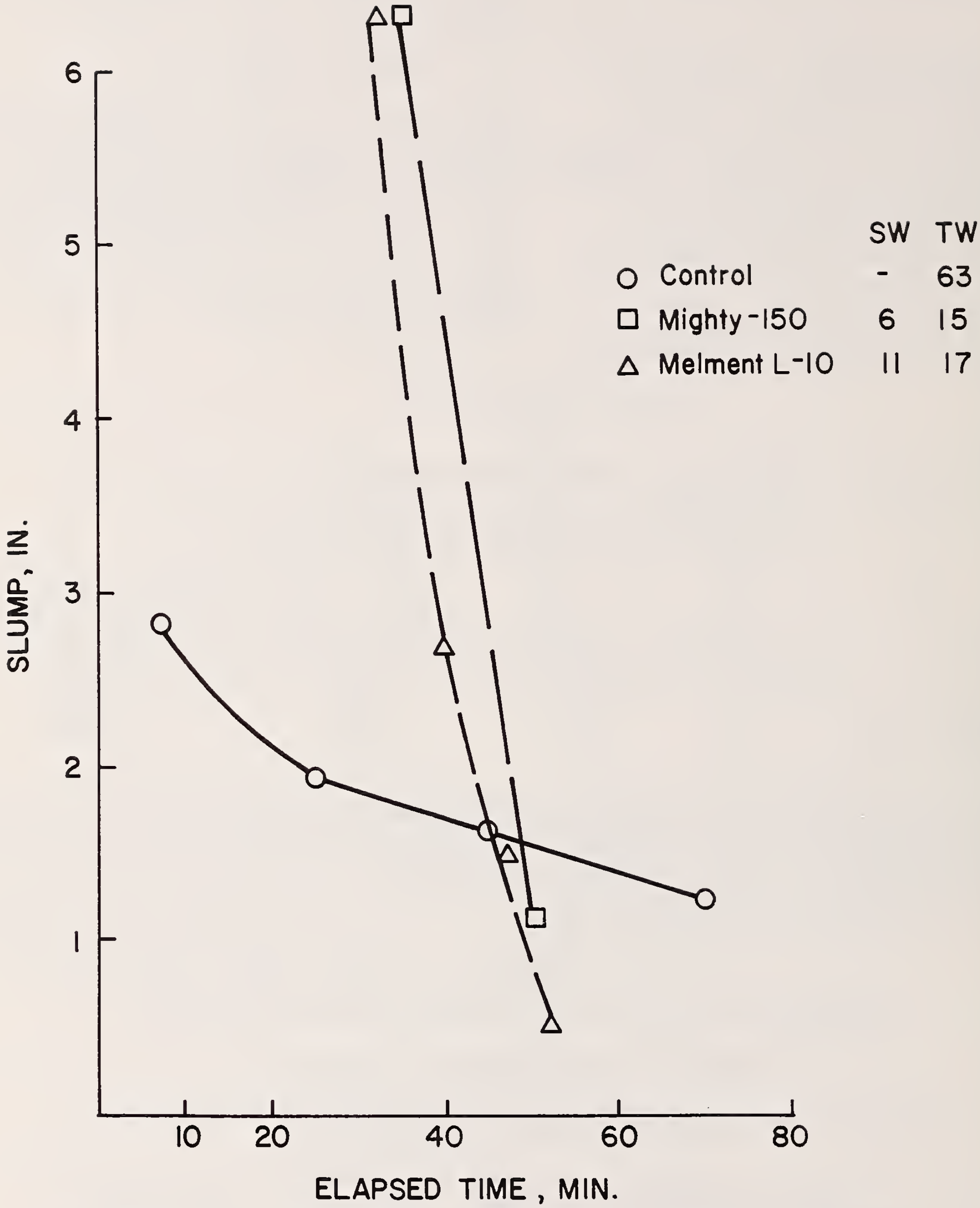

FIGURE 49. SLUMP LOSS IN CONCRETES PRODUCED IN READY-MIX TRUCK

7.2.1 Materials and Mixing Procedures

A Type I cement was used for all mixtures. As the trials were conducted during a period of severe cement shortage, the cement was ordered in bag quantities and stored at the yard until ready for use. The investigators had to resort to manual addition of cement to the R-M truck, as the producer was obtaining cements from a number of suppliers at the time, and could not guarantee that his bins would contain the same cement from one day to the next. Chemical analysis of the bag cement is shown in Table 45.

TABLE 45

Chemical Analysis of Type I Cement

R-M Trials

C_3S - %	-	56.49
C_2S - %	-	14.81
C_3A - %	-	8.79
C_3A (via XRD) - %	-	4.0
C_4AF - %	-	7.79
SO_3 - %	-	2.83
Alkalies (as Na_2O) - %	-	0.79
Blaine Fineness - cm^2/g	-	4,260

Mini-slump testing indicated that this cement required 0.77% (s/c) of Mighty-150 in order to achieve 30% water reduction. This is a higher dosage requirement than for many of the other cements used previously in this study, and is attributed to the combination of moderately high C_3A and high alkali content and fineness of this cement.

The aggregates used were the sand and gravel (3/4 in (19 mm) maximum) normally available at the local yard. Properties are shown below.

TABLE 46

Aggregate Properties

R-M Field Trials

	Specific Gravity	Absorption %	Moisture Content %
Sand	2.72	1.20	6.0
Gravel (1 in.1/ top size)	2.72	1.80	1.8

1/ To convert from in. to mm multiply by 25.4.

SWR admixtures were pumped out of the drums stored in our labs into 5 gal (18.9 L) containers and transported to the R-M yard. The air-entraining agent used was Daravair[R 1/], which is normally used at this particular yard.

Control concrete mixtures were designed for 658 lb/yd^3 (391 kg/m^3) of cement, 2-3 in. (51-76 mm) of slump, and air content of 5-6%. SWR mixtures were designed for initial slump of 5-6 in. (127-152 mm), air content of 6-7%, and cement content of 658 lb/yd^3 (391 kg/m^3). The dosage of SWR was adjusted so as to achieve a net water-cement ratio less than 0.35 at the specified slump.

Mix proportions for control, Mighty-150 and Melment L-10 mixtures are shown in Table 47. Dosage levels are consistent with the relatively high requirements indicated by the mini-slump test.

Mix procedure was as follows: sand, gravel, Daravair, plus 60-75% of the mix water was loaded into the truck at the batch plant, then bagged cement and the remaining water were added by hand and the truck was given 70 revolutions (5 minutes) at mixing speed. For the control mix slump, air, and unit weight were taken immediately after cessation of mixing. Specimens were made at this time. For the SWR mixes the truck was allowed to run at agitation speed for 20 minutes, then the SWR was added by hand. The truck was then remixed 70 revolutions at mixing speed. Air, unit weight, and initial slump were determined immediately after cessation of this mix period. Specimens were also cast at this time.

Properties of the fresh concrete mixtures are shown in Table 48. All properties were within desired limits with the exception of the air content of the Melment L-10 mixture. This represented the fifth trial, and as cement supplies were exhausted further batches could not be prepared.

7.2.2 Slump Loss and Setting Time

Slump loss curves for control, Mighty-150, and Melment mixtures are shown in Figure 49. Slump loss is extremely rapid, working times for both SWR mixes are less than 20 minutes. These high rates of slump loss are most probably due to the relatively warm temperatures coupled with the high C_3A, alkalies and fineness of the cement. Additionally, the batches were held somewhat longer prior to addition of SWR than in

1/ [R]Registered Tradmark, W. R. Grace and Company, Cambridge, MA.

TABLE 47

Mix Proportions - R-M Field Trials

Mix	SWR	Dosage (% s/c)	A/E Agent (ml/lb) 1/	w/c Ratio	Quantities (lb/yd^3) 2/ Water	Cement	Sand	Gravel	% Sand Abs. Vol.
1	None	-	0.3	0.39	258	655	1,175	1,901	38
2	Mighty-150	0.60	1.2	0.32	216	669	1,179	1,942	38
3	Melment L-10	0.58	1.0	0.32	217	677	1,193	1,964	38

1/ To convert from ml/lb to ml/kg multiply by 2.20
2/ To convert from lb/yd^3 to kg/m^3 multiply by 0.594

TABLE 48

Properties of Fresh Concrete

R-M Field Trials

Mix	SWR	Slump (in.) 1/	Air Content (%)	Unit Weight (lb/ft^3) 2/	Temperature (^{o}F) 3/
1	None	2.8	5.2	148	81
2	Mighty-150	6.3	6.5	146	84
3	Melment L-10	6.3	5.5	147	83

1/ To convert from in. to mm multiply by 25.4.

2/ To convert from lb/ft^3 to kg/m^3 multiply by 16.038.

3/ ^{o}C = 5/9(^{o}F - 32)

the laboratory studies at elevated temperatures (see Figure 39).

Time-of-set data were gathered through the use of a portable Proctor penetrometer device. Results, shown in Table 49, display considerable set acceleration in the mixtures containing SWR. Although some accelerative effect had been seen in previous studies with Melment L-10, Mighty-150 does not typically cause acceleration of set. Just as retardation was found to reduce the rate of slump loss, in this particular case the increased rate of slump loss was found to be correlated with an acceleration of set.

7.2.3 Other Tests

A few 6x12-in. (152x305 mm) specimens were cast for determination of 7-day compressive strength. Results are shown in Table 50.

TABLE 49

Setting Times

R-M Field Batches

Mix	SWR	Setting Time Initial (hr:min)	Final (hr:min)
1	None	2:25	3:20
2	Mighty-150	2:00	2:25
3	Melment L-10	1:50	2:15

The increases in strength (18% and 13%) are less than would be expected from the differences in water-cement ratio between controls and SWR concretes. Compressive strength data for similar concretes prepared in the laboratory (see Section 9.2.2, Table 62), indicate an increase of 35% and 43% in 7-day compressive strength

TABLE 50

Compressive Strength at 7-Days

R-M Field Batches

Mix	SWR	Compressive Strength (psi)	w/c Ratio
1	None	4,000	0.39
2	Mighty-150	4,720	0.32
3	Melment L-10	4,500	0.32

1/ To convert from psi to MPa multiply by 6.894×10^{-3}.

for Mighty-150 and Melment L-10, respectively, for approximately the same decrease in water-cement ratio.

Specimens were also cast for determination of freeze-thaw (ASTM C666: Procedure A) and deicer scaling (ASTM C672) resistance. Early in the test program extensive popouts were noted in all specimens. Evidently, the aggregates used for these tests had poor durability, therefore, the testing was discontinued. Concrete prisms cast on-site were transported to the laboratory, sawed, lapped and subjected to linear traverse analysis (ASTM C457-71). Data are shown in Table 51.

Characteristics of the air-void system for all concretes were excellent. The void spacing factors for the SWR mixes are perhaps the lowest ever reported for concretes containing these admixtures. It is quite possible, though difficult to substantiate, that the high rates of slump loss and setting in these mixtures "froze-in" the air void system and prevented coalescence of smaller air bubbles into larger ones in the plastic state.

8. The Air-Void System in Concrete Containing Super-Water Reducers

Resistance to freezing and thawing and application of deicing salts is required for all concrete used in highway applications. In order to achieve this resistance, a high quality entrained air-void system must be developed in the concrete through the use of approved air-entraining agents. The American Concrete Institute has set forth certain characteristics of the air-void system which must be met by any concrete used in severe environments where deicing salts are in general use. These guidelines (ACI 345-17) require:

1. A calculated spacing factor less than about 0.008 in. (0.20 mm).

2. A surface area of the air voids greater than about 600 in.^{2}/in.^{3} (23.6 mm^2/mm^3) of air-void volume.

3. A number of air voids per linear inch of traverse significantly greater than the numerical value1/ of the percentage of air in the concrete.

It has become apparent that many concretes containing super-water reducers do not meet these criteria. Tynes (21) reported spacing factors of 0.008 to 0.012 in. (0.20 to 0.30 mm) in low water-cement ratio concretes prepared with Mighty-150, Melment L-10, and Lomar-D. Poor durability of specimens subjected

1/ In SI units this would require the number of air voids per linear mm to be significantly greater than the numerical value of the percentage of air in the concrete multipled by 0.0394.

TABLE 51

Air Contents and Air-Void Parameters

R-M Field Batches

Mix	SWR	Air Content (%)	Voids per inch1/	Specific Surface (in.^{2}/in.^{3})2/	Void Spacing Factor (in.)3/
1	None	3.1	8.3	1,063	0.0057
2	Mighty-150	4.3	14.2	1,310	0.0038
3	Melment L-10	3.7	13.0	1,418	0.0038

1/ To convert from voids per inch to voids per mm multiply by 0.0394.

2/ To convert from in.^{2}/in.^{3} to mm^2/mm^3 multiply by 0.0394.

3/ To convert from in. to mm multiply by 25.4.

to rapid freeze-thaw was attributed to these high spacing factors. Likewise, Whiting (9) has reported high spacing factors in water-reduced concretes yet in this case durability was adequate. Mielenz and Sprouse (23) have reported varying results. In some cases high spacing factors lead to decreased durability, in other cases durability was adequate even with spacing factors as high as 0.013 in. (0.33 mm). Also, these latter workers found a decrease in spacing factors in SWR concretes below the accepted value of 0.008 in. (0.20 mm), when initial air contents of 7-8% were employed.

The objective of this phase of the project was to develop reliable procedures for ensuring the production of concretes which meet the ACI criteria for air-void systems when SWR are used. Among these variables studied were type and dosage of air-entraining agent, sequence of addition of air-entraining agent, use of vibration, and use of high initial plastic air contents.

8.1 Screening Tests

Most of the reported studies concerning the poor air-void distributions obtained when SWR were added to air-entrained concretes utilized conventional A/E agents based on neutralized Vinsol resin (sodium soap of pine wood resin), or synthetic aryl alkyl sulfonates. It was considered worthwhile to investigate the air-void systems obtained when other surfactants are used to obtain air entrainment. As the preparation of full-size concrete specimens would have entailed an expense out of proportion to such an initial study, air-entrained mortars were used for these investigations.

The surfactants chosen were obtained from a local supplier, Stepan Chemical Company, Northfield, Illinois. In addition, neutralized Vinsol resin plus two formulations of Darex[R] Air-Entraining Agent (W. R. Grace and Company, Cambridge, Massachusetts) were used. Trade names, generic class, and mixture numbers of the various products are shown in Table 52. Mix No. 0 was prepared without SWR (Mighty-150).

TABLE 52

Surfactants Used in Air-Entrained Mortars

No.	Product	Generic Description
0	NVR	Sodium soap of pine wood resin (sodium abietate)
1	NVR	Sodium soap of pine wood resin (sodium abietate)
2	Darex[R]-New Formulation	p-alkyl benzene sulfonate
3	Darex[R]-Old Formulation	triethanolamine salt of a sulfonated hydrocarbon
4	A-18	sodium alkenyl sulfonate
5	B-1	ammonium alkyl phenol ethoxylate
6	B-13	alkyl alkoxysulfate, ammonium salt
7	B-20	lauryl polyethoxysulfate, ammonium salt
8	B-22	lauryl polyethoxysulfate, ammonium salt
9	B-28	alkyl polyalkoxysulfate, sodium salt
10	Ninol - 1285	diethanolamide of coconut and oleic fatty acids
11	Stepan Flote - 24	cetyl-stearyl sulfate sodium salt
12	Amidox C-2	ethoxyethyl monoethanolamide
13	Petrostep - 450	petroleum sulfonate, sodium salt
14	Bioterge AS-40	40% sodium alpha olefin sulfonate

As all of the proprietary admixtures (Mixes 4-14) were supplied in concentrated form, they were diluted 1:100 by volume prior to use in mortar mixtures.

The mortar mix was similar to that used in ASTM C185-75, with somewhat more sand being used so as to approximate a typical concrete mix having a cement content of 564 lb/yd^3 (335 kg/m^3). Water-cement ratio of the control mortar was 0.6, water-cement ratio of the mortars containing Mighty-150 was 0.5. Dosage of Mighty-150 used in all mortars (except mixture 0) was 0.56% by weight of cement. Dosage of A/E agent was adjusted so as to achieve an initial plastic air content of

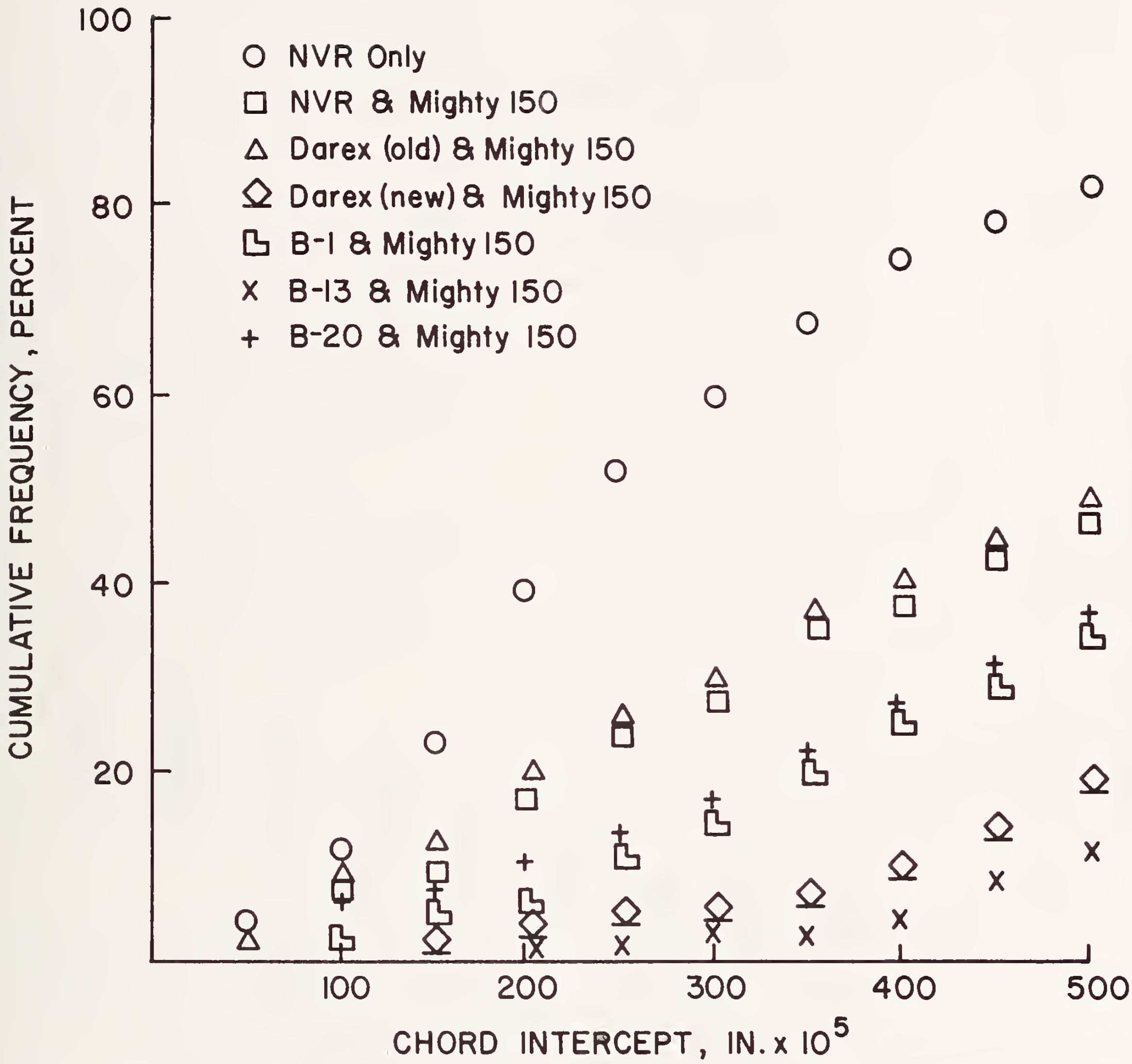

FIGURE 50. CUMULATIVE FREQUENCY OF CHORD INTERCEPTS, AIR ENTRAINED MORTARS

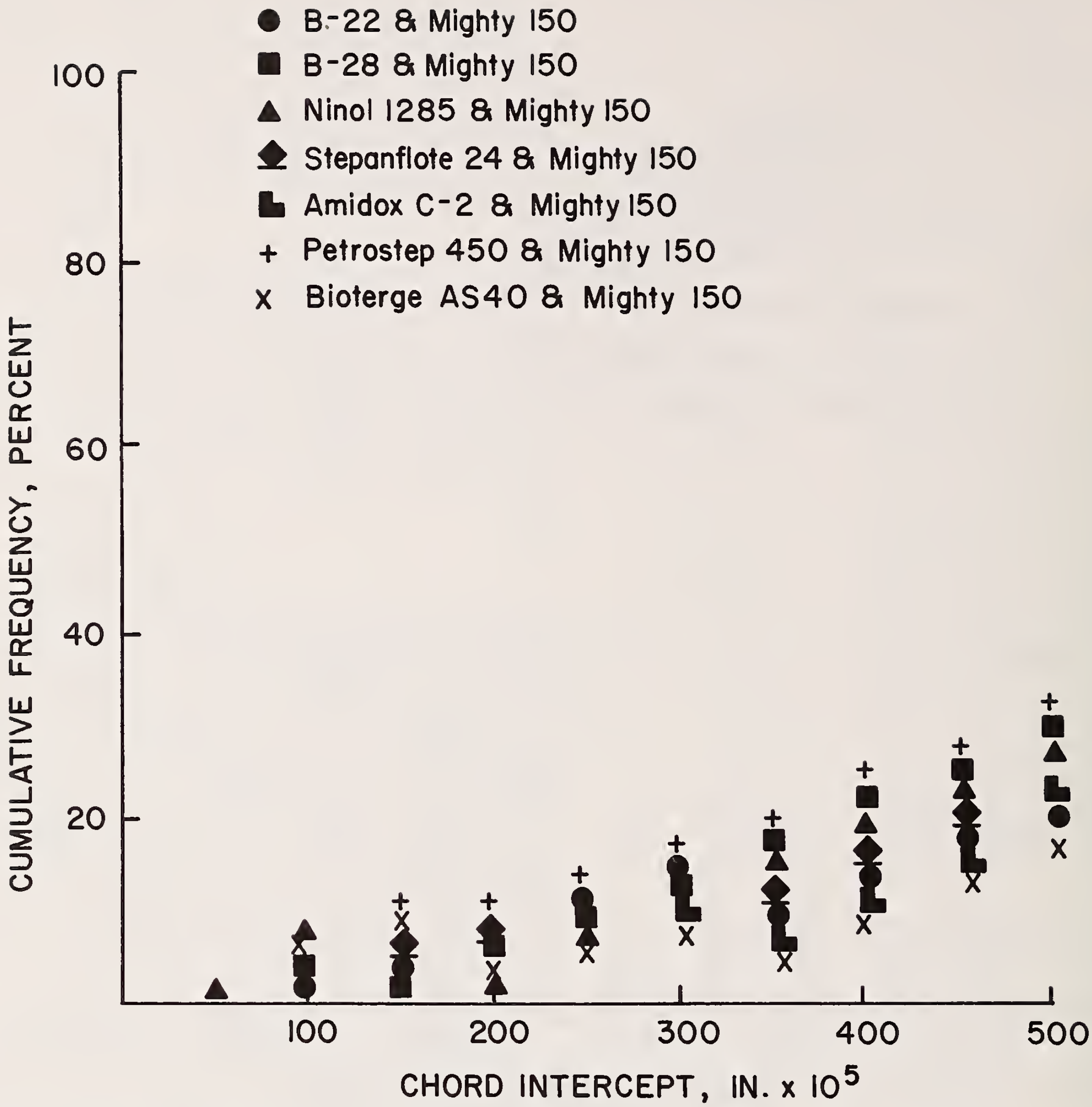

FIGURE 50. (CONT.) CUMULATIVE FREQUENCY OF CHORD INTERCEPTS. AIR ENTRAINED MORTARS

about 16-20 percent determined via ASTM C185-75 (gravimetric).

The mix cycle prescribed in ASTM C305-65 was used to prepare the mortars. Cement and water were added to the mixing bowl and the mixer run at slow speed (140 rpm) for 30 seconds. The sand was then added while mixing for an additional 30 seconds. The speed was then increased to medium (285 rpm), and the Mighty-150 was added, followed by the A/E agent. Mixing was continued for an additional 30 seconds. The mixer was then stopped and covered for 1.5 minutes. The final mix period was 1 minute at medium speed (285 rpm).

Specimens were cast as 40x40x160 mm prisms. These were allowed to harden overnight, then placed under water at 160°F (71°C) for 40 hours. The hot water cure imparted sufficient strength to the specimen so that lapping could be carried out without pull-out of sand grains from the surfaces. After curing the specimens were cut in two lengthwise, then the interior surface was lapped.

Analysis of the air-void system was carried out with equipment and techniques normally used on larger concrete prisms (ASTM C457-71). Hardened air contents, along with plastic air content and A/E agent dosages are presented in Table 53.

TABLE 53

Mixture Characteristics

Air-Entrained Mortars 1/

Mix	A/E Agent Dosage (% s/c)	Air Content, % Plastic	Air Content, % Hardened	
0	0.011	19.7	18.6	(Control)
1	0.011	17.7	11.5	
2	0.010	17.2	12.5	
3	0.010	16.6	11.8	
4	0.005	17.2	15.3	
5	0.002	21.1	10.8	
6	0.0001	18.7	18.0	
7	0.011	20.3	14.5	
8	0.0011	19.4	12.6	
9	0.0011	18.5	9.2	
10	0.0011	17.6	7.7	
11	0.010	17.7	11.3	
12	0.008	17.5	11.8	
13	0.006	18.2	6.3	
14	0.006	18.5	8.1	

1/ For all mixes (1-14)
Cement (Type I blend) = 360 gm
Ottawa Sand = 1,518 gm

For most of the mixtures containing Mighty-150 a large loss of air between the plastic and hardened states was observed. This was true of the commercial A/E agents (Mixtures 1, 2, 3) as well as the proprietary sufactants. The only A/E agents which appeared to contribute to a retention of air content similar to that observed in the controls were A-18 (Mixture 4) and B-13 (Mixture 6).

Initial calculations of specific surface, voids per inch, and spacing factor were carried out on some control and SWR specimens. The values were numerically much different from data typically obtained on concrete specimens. For example, spacing factor for the control specimen was 0.002 in. (0.05 mm), while that for the specimen containing NVR plus Mighty-150 was 0.005 in. (0.13 mm). These are much lower than normally encountered in practice, and can be attributed to the high air content present in the paste phase in these specimens (approximately 40% by volume of paste) as opposed to typical concretes where air content is approximately 20-25% of the paste volume. Data on these mixes, therefore, are presented in graphical terms as cumulative frequency distribution of air voids rather than in the conventional terminology used in linear traverse of concrete. These cumulative frequency distributions are plots of the chord intercepts versus their cumulative frequency of occurrence, in percent, and give a rapid indication to the reader of the nature of the void size distribution, and the change brought about in this distribution by use of various A/E agents. In well proportioned, suitably air-entrained, rich concretes mixtures a large majority (greater than 80%) of the entrained air voids will exhibit chord intercepts less than 500 X 10^{-5} in. (130 μm). Within this size range, the larger proportion of voids will be found with intercepts between 50-250 X 10^{-5} inches (10-60 μm). Reference to Figure 50 indicates that the control specimen (NVR only) exhibits a chord intercept distribution closely resemblying that in such a concrete. All of the specimens containing the SWR, however, exhibit decidedly inferior distributions. Even those admixtures which exhibited good retention of air content, (B-13 and A-18) show only a minority of chords less than 500 X 10^{-5} in. (130 μm). "Best" results are obtained for combinations of NVR and the original Darex formulation with Mighty-150, but even these are inferior to the curve with NVR alone.

The results of this screening series, therefore, substantiate the findings obtained in the aforementioned concrete

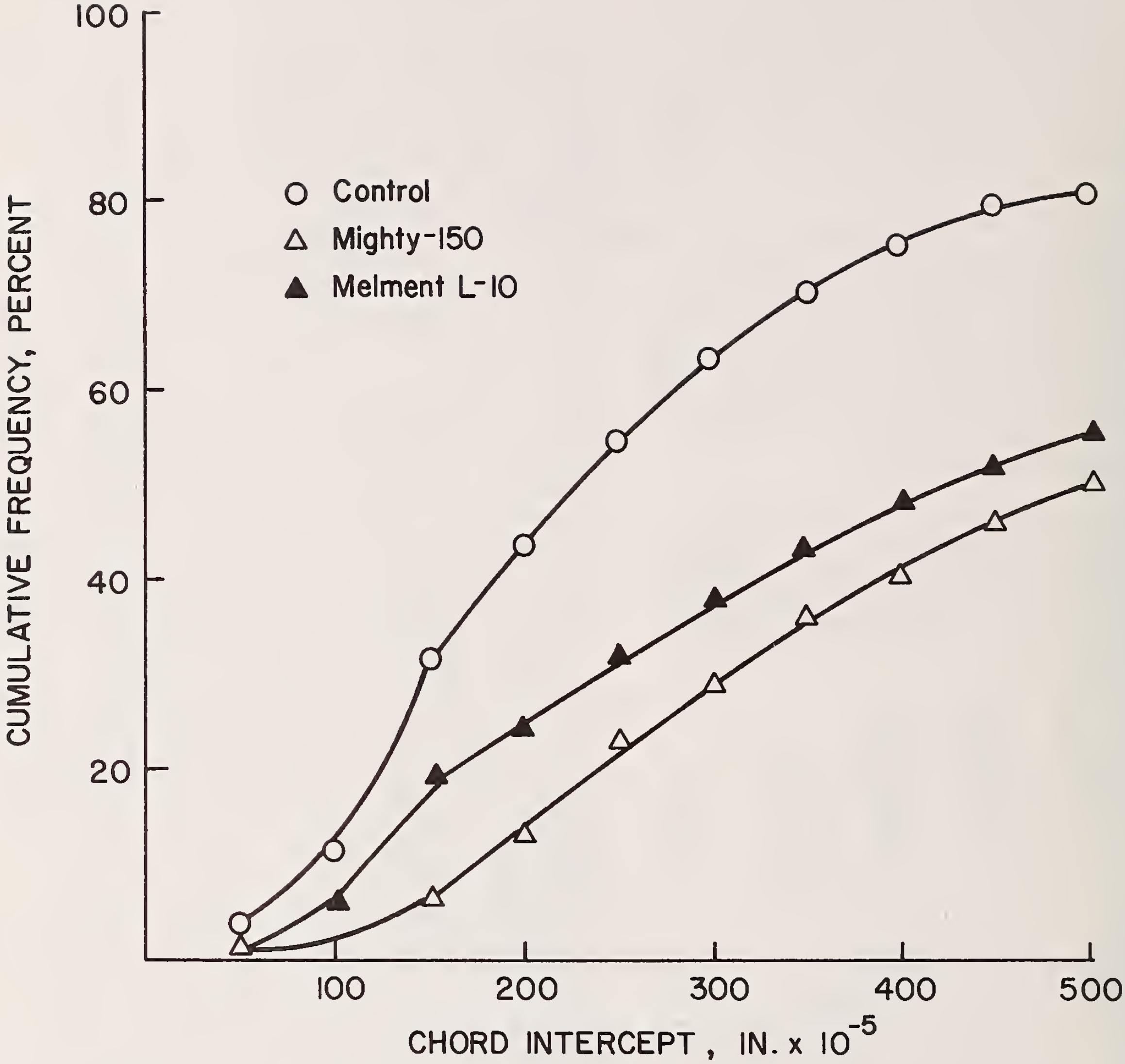

FIGURE 51. CUMULATIVE FREQUENCY OF CHORD INTERCEPTS. PAVEMENT CONCRETE MIXTURES

studies. That is, the use of SWR in combination with either conventional or novel air-entraining agents brings about a shift in the air-void distribution towards larger void sizes, and also, in many cases, causes a loss of air between the plastic and hardened states. These two facts indicate a possible mechanism for this effect. The lower mixture viscosity effected by the addition of SWR to the concrete should make it easier both for air bubbles to escape from the concrete and for smaller bubbles to coalesce into larger ones. Chemical effects, though secondary, may also be operative, as evidenced by the somewhat better void size distribution evidenced in the NVR Mighty-150 mixtures as opposed to the other A/E agents.

8.2 Initial Concrete Mixtures

Linear traverse analyses (ASTM C457-71) were performed on specimens cast from the concrete mixtures described in Section 4.2 (Table 11, page 31). Results are given in Table 54. Control mixtures (P-1, P-2, B-1, B-2) exhibit air-void characteristics passing all the requirements of ACI 345-17. On the other hand mixtures containing SWR exhibit specific surface data lower than that recommended by ACI, and void spacing factors exceeding the recommended limit of 0.008 in. (0.20 mm). This is in spite of the fact that hardened air contents were equal to or, in the majority of cases, higher than the corresponding control mixtures. A mixture in which the addition of Mighty-150 was delayed until the second mix period of the 3-3-2 mix cycle (PM-2D) showed no improvement in air-void parameters.

Cumulative frequency diagrams for chord intercepts of pavement mix control, Mighty-150, and Melment L-10 mixtures are shown in Figure 51. These are very similar to results obtained on the air-entrained mortars (see Figure 50). As before control mixtures showed roughly 80% of the chord intercepts less than 500 X 10^{-5} in. (130 μm), while specimens containing SWR showed only about 50% of the intercepts in this range. These results support the hypothesis that the degradation in air-void characteristics is indeed caused by a shift in bubble size distribution to larger diameters when SWR are added to air-entrained concrete.

8.3 Effects of Vibration on Air-Void Characteristics

It is known that air contents of conventional concretes can be reduced during placement under heavy vibration. Powers (23) has shown that during vibration there is a preferential loss of air bubbles in the larger size categories. Backstrom, et al (24) believed that these large bubbles in addition to being expelled from the mix, could also be split by vibration into smaller voids. These earlier studies have a direct bearing on this project as they indicate that the shift in void size distribution due to SWR might be reversed under the influence of vibration. As vibration might reduce the total air content below desirable levels, use of a relatively high initial air content, followed by vibration to achieve specified air contents, was considered a promising avenue of approach. The first attempt utilized a mixture containig Melment L-10 designed similar to that of Mix No. PL-1, but having an initial plastic air content of 13%. The mixture was then internally vibrated for 4 minutes using a spud vibrator. Air content was then measured to be 7%. Linear traverse results on a specimen cast from this mixture, shown in Table 55, indicate a marked improvement in air-void parameters.

In view of these promising initial results, a more detailed series was initiated. A description of these mixtures follows:

For all mixtures Melment L-10 was added at the start of the second mix (3-3-2), NVR was added 30 seconds later.

Mixture	Description
L	Initial air content of 9.1%. Specimen cast immediately.
L-1	Batch L vibrated internally for 30 seconds. Air content reduced to 5.6%. Specimens then cast.
L-2	Batch L vibrated internally for 1 minute. Air content reduced to 3.1%. Specimen then cast.
L-V	Batch L repeated. Initial air content of 8.5%. Slump loss cycle (20 minute rest - 2 minute remix) carried out to 60 minutes. Air content reduced to 5.5% at 60 minutes. Specimen then cast.
L-V-1	Batch L-V vibrated 1 minute. Air content reduced to 2.8%. Specimen then cast.
L-V-2	Batch L-V repeated. NVR added after 60 minutes of slump loss cycle to bring air content to 8.7%. Vibrated 1 minute internally to reduce air content to 4.6%. Specimen then cast.

L-V-3	Batch L-V repeated. NVR added after 40 minutes of slump loss cycle to bring air content to 9.7%. Vibrated 1 minute internally to reduce air content to 5.3%. Specimen then cast.

Results of linear traverse analyses are given in Table 56. The batch with high initial air content (L) shows good air void parameters. Vibration to more moderate air levels (L-1, L-2) reduces the number of voids per inch but their

TABLE 54

Air Contents and Air-Void Parameters

Initial Concrete Mixtures

Mix	Description	SWR	Air Content (%)	Voids per inch1/	Specific Surface $(in.^2/in.^3)$ 2/	Void Spacing Factor (in.) 3/
P-1	Paving Mix - Type I Cement	None	3.7	8.5	928	0.0059
P-2	Paving Mix - Type II Cement	None	3.5	9.1	1,025	0.0053
B-1	Bridge Deck Mix - Type I Cement	None	5.3	12.4	937	0.0052
B-2	Bridge Deck Mix - Type II Cement	None	5.2	12.4	1,029	0.0047
PM-1	Paving Mix - Type I Cement	Mighty-150	4.3	4.4	414	0.0110
PM-2	Paving Mix - Type II Cement	Mighty-150	5.8	6.3	430	0.0086
PM-2D	Paving Mix - Type II Cement	Mighty-150	5.0	5.2	415	0.010
BM-1	Bridge Deck Mix - Type I Cement	Mighty-150	5.8	7.2	497	0.0089
BM-2	Bridge Deck Mix - Type II Cement	Mighty-150	5.2	6.8	521	0.0087
PL-1	Paving Mix - Type I Cement	Melment L-10	3.9	4.8	502	0.010

1/ To convert from voids per inch to voids per mm multiply by 0.0394.

2/ To convert from $in.^2/in.^3$ to mm^2/mm^3 multiply by 0.0394.

3/ To convert from in. to mm multiply by 25.4.

TABLE 55

Air-Void System Parameters

Internal Vibration of High-Air Mixture

Mixture	Air Content (%)	Voids per inch1/	Specific Surface $(in.^2/in.^3)$ 2/	Void Spacing Factor (in.) 3/
PL-1A	6.6	13.6	830	0.0041

1/ To convert from voids per inch to voids per mm multiply by 0.0394.

2/ To convert from $in.^2/in.^3$ to mm^2/mm^3 multiply by 0.0394.

3/ To convert from in. to mm multiply by 25.4.

TABLE 56

Air Contents and Air-Void Parameters

Vibration Series

Mixture 1/	Air Content (%)	Voids per inch 2/	Specific Surface ($in.^2/in.^3$) 3/	Void Spacing Factor (in.) 4/
L	7.3	10.2	561	0.0053
L-1	5.0	8.1	650	0.0069
L-2	5.1	7.9	621	0.0070
L-V	5.4	6.4	474	0.0087
L-V-1	3.8	4.2	443	0.0114
L-V-2	4.8	9.9	835	0.0054
L-V-3	6.6	11.5	702	0.0049

1/ See page 95 for description of mixtures.

2/ To convert from voids per inch to voids per mm multiply by 0.03^4.

3/ To convert from $in.^2/in.^3$ to mm^2/mm^3 multiply by 0.0394.

4/ To convert from in. to mm multiply by 25.4.

specific surface and void spacing factors are still within recommended limits. Subjecting the high air content batch to extended mixing (L-V) followed by vibration (L-V-1), however, degrades the quality of the air void system. Adding A/E agent to this mix at 60 and 40 minutes brings the air-void system back into the acceptable range, even after 1 minute of internal vibration.

An examination of air void distribution data (not shown) for these mixtures indicated that larger air voids had not been preferentially driven from the mix under the influence of vibration. Cumulative frequency distributions (in terms of percent) were similar to the initial mix (PL-1) where conventional air content was used. The improvement in air void distribution in the high air and vibrated mixtures is, therefore, attributable solely to the increased hardened air contents in this series of specimens, and not to the hypothesized shift in air-void distribution brought about by vibration. The results do indicate, though, that use of higher then normal initial plastic air contents may allow one to achieve a proper air-void distribution in concretes containing SWR. Further work along these lines will be described in a later section of this report.

8.4 Effects of Addition Sequence of A/E Agent and SWR on Characteristics of Air-Void Systems

During this phase of the research information was received through a manufacturer of SWR that confidential tests had indicated the sequence of addition of A/E agent and SWR might have an influence on development of a proper air-void distribution. To test this hypothesis a series of mixtures using the "pavement" mix design was prepared using neutralized Vinsol resin (NVR) as A/E agent and Melment L-10 as SWR. In all cases, the Melment L-10 was added at the beginning of the second mix cycle (3-3-2). Design plastic air content was 6 ± 1%. NVR was added at various points in the mix cycle, as described below:

Mixture	Description
LS-0	NVR added to aggregates
LS-1	NVR added to mix water
LS-2	NVR added 30 seconds after Melment
LS-3	NVR added 2 minutes after Melment
LS-4	NVR added 4 minutes after Melment
LS-5	NVR added 10 minutes after Melment
LS-6	NVR added 20 minutes after Melment

Results of linear tranverse analyses showed no significant difference between any of the mixtures. Spacing factors ranged from 0.009 to 0.015 in. (0.22 to 0.38 mm) all above the recommended maximum of 0.008 in. (0.20 mm). Obviously, in this series no significant improvement in the air-void system was effected by varying the addition sequence of A/E agent and SWR.

8.5 Further Investigations into Use of Higher Air Contents Using Laboratory Mix Cycle

Results of the previous section indicated that the use of high initial air contents in the fresh concrete might be one means of obtaining a satisfactory air-void system. To date, however, only one combination of A/E Agent, SWR, and cement had been investigated (NVR/Melment L-10). Also, the effect of extended mixing (slump loss cycle) was not fully addressed. Toward these ends, "pavement mix" batches were prepared using Melment L-10, Mighty-150, and the two cements used in the initial studies (Nos. 21795 - Type I and 21796 - Type II). SWR were added at the beginning of the second mix cycle (3-3-2). A/E agent (NVR) was added 30 seconds after introduction of the SWR. Specimens were cast immediately after determination of initial air content, and then again after slump had dropped to 2-3 inches (50-76 mm).

Results giving initial air (plastic) contents, hardened air contents, and air-void system parameters are shown in Table 57. Although void spacing factors and numbers of voids per inch are acceptable, specific surface data are less than the recommended 600 in.^{2}/in.^{3} (24 mm^2/mm^3) in all but one instance. These lower specific surfaces can be attributable to the coarser void system found in SWR concrete. The effect of casting the specimens after slump had reached 2-3 inches, which was about 40 minutes into the slump loss cycle, was to raise the void spacing factor, decrease hardened air content and number of voids per inch, as expected. In each case, however, void spacing factors were still within the recommended limit, thus indicating that loss of air during transport might not be deleterious if final hardened air contents remained close to 6%.

8.6 Air-Void System in Concretes Prepared Using Simulated Field Mixing Cycles

As with the slump loss investigations, more data was needed on the air void systems of concretes prepared using the simulated field mix cycles described in Section 5. Mixtures were prepared using "Central Mix", "Ready Mix", and "Iowa"

TABLE 57

Air Contents and Air-Void System Characteristics

Mixtures Using High Initial Air Contents

SWR	Cement	Time of Casting 1/	Plastic Air Content (%)	Hardened Air Content (%)	Voids per inch 2/	Specific Surface (in.^{2}/in.^{3}) 3/	Void Spacing Factor (in.) 4/
Mighty-150	Type I	Immediate	9.3	7.7	10.9	567	0.0050
Mighty-150	Type I	40 min.	5.9	5.9	8.2	557	0.0068
Melment L-10	Type I	Immediate	9.3	9.2	12.8	556	0.0042
Melment L-10	Type I	40 min.	5.9	4.9	9.1	737	0.0060
Mighty-150	Type II	Immediate	9.3	10.2	12.2	478	0.0042
Melment L-10	Type II	Immediate	9.1	7.3	10.6	579	0.0050

1/ Time from start of initial mixing.

2/ To convert from voids per inch to voids per mm multiply by 0.0394.

3/ To convert from in.^{2}/in.^{3} to mm^2/mm^3 multiply by 0.0394.

4/ To convert from in. to mm multiply by 25.4.

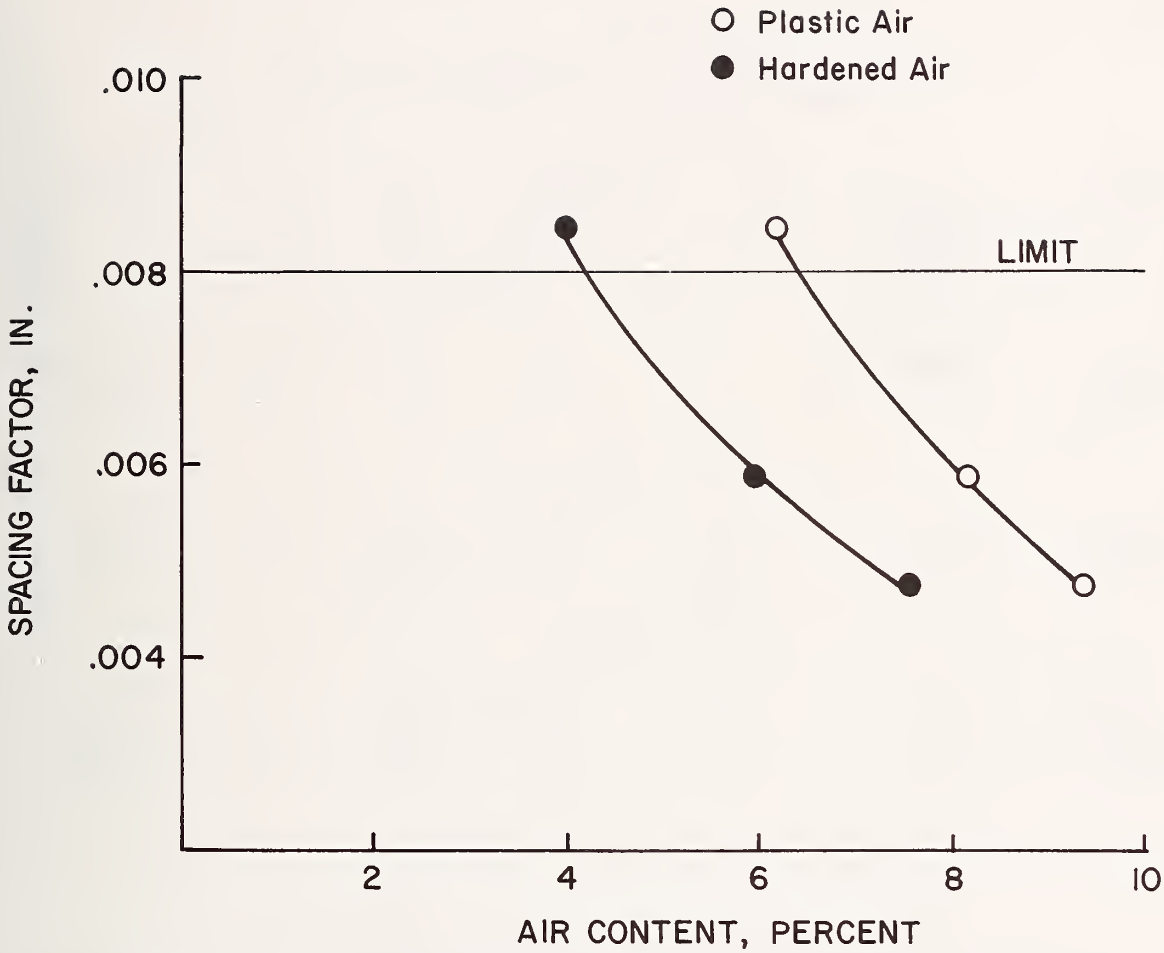

FIGURE 52. RELATIONSHIP BETWEEN AIR CONTENT AND SPACING FACTOR

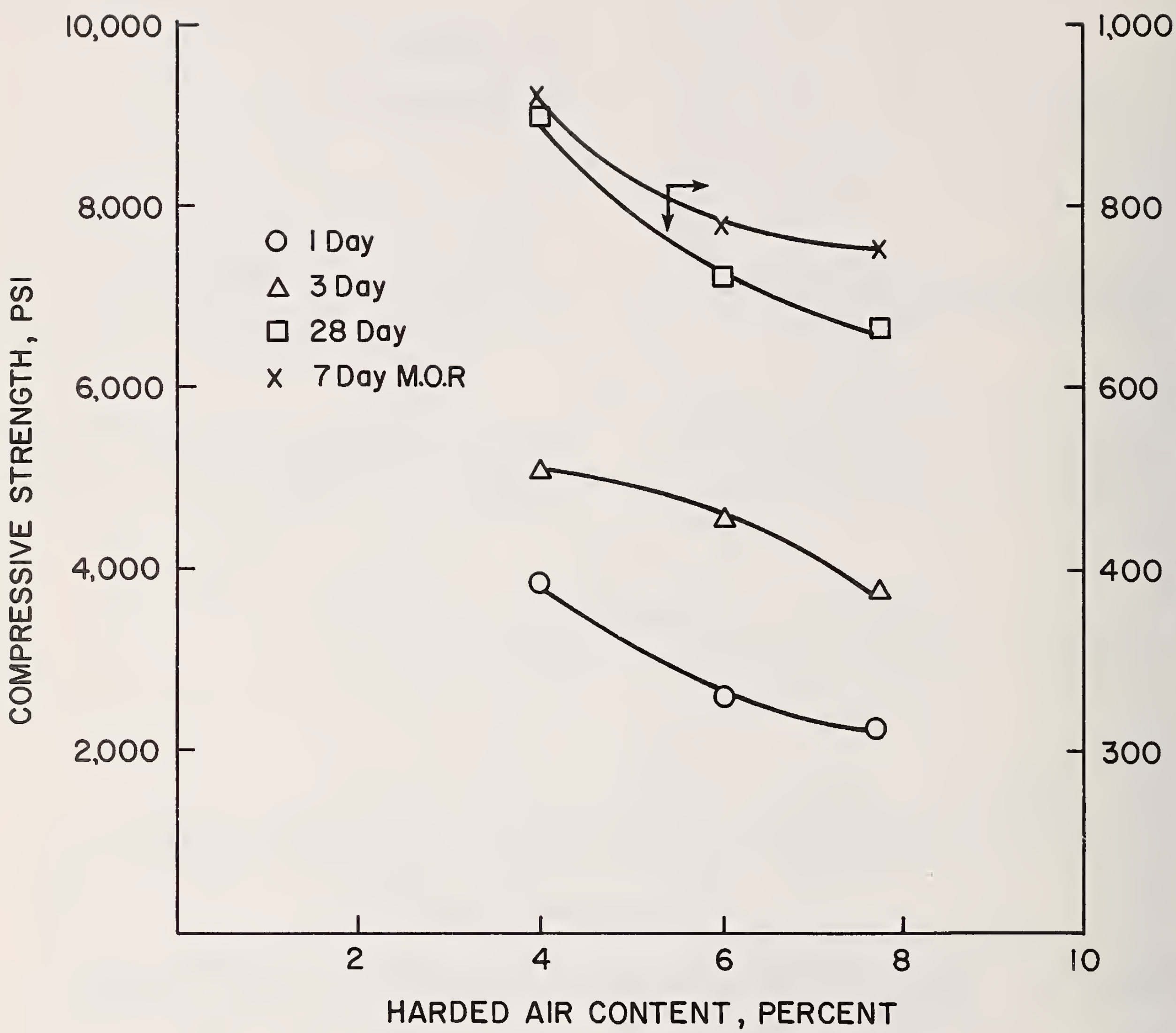

FIGURE 53. INFLUENCE OF HARDENED AIR CONTENT ON COMPRESSIVE AND FLEXURAL STRENGTH

mix designs and mix cycles previously described. Cement Lot No. 21802 (see Appendix D) was used for all mixtures. Air contents for the majority of the mixtures were held to normal levels (6 ± 1%), with the exception of mixtures ROA-21-32, where initial air contents were increased. The mixture notation is the same as that used in Section 5. Results are shown in Table 58.

plastic air content. The relationship between hardened air content, plastic air content, and spacing factor is shown in Figure 52. For this particular mixture use of an initial plastic air content of about 7% should yield an acceptable air-void system. At this level of plastic air, hardened air content would be about 5%.

TABLE 58

Air Contents, Slump, and Air-Void Characteristics
Simulated Field Mix Cycles

Mixture	Slump (in.)1/	Plastic Air Content (%)	Hardened Air Content (%)	Voids per inch2/	Specific Surface ($in.^2/in.^3$)3/	Void Spacing Factor (in.)1/
Controls						
C-1	2.6	5.5	3.7	4.8	525	0.0104
R-1	3.1	5.9	4.1	9.4	909	0.0060
I-1	0.7	5.3	4.3	11.7	1,101	0.0051
Mighty-150						
MC-1	3.1	5.4	4.0	3.8	380	0.0129
RM-1	3.7	6.0	5.0	4.9	393	0.0120
IM-1	3.1	6.8	4.8	11.9	1,005	0.0053
Effect of Air						
RM-12	4.9	6.1	4.0	6.2	625	0.0084
ROA-21	5.9	8.1	6.0	10.8	715	0.0059
ROA-22	1.5	5.6	4.8	7.1	594	0.0081
ROA-31	5.8	9.2	7.7	13.1	675	0.0047
ROA-32	3.2	6.9	5.8	8.1	558	0.0079

1/ To convert in. to mm multiply by 25.4.

2/ To convert from voids per inch to voids per mm multiply by 0.0394.

3/ To convert from $in.^2/in.^3$ to mm^2/mm^3 multiply by 0.0394.

The control mixtures for "ready mix", and "Iowa" overlays show good air-void systems. Results for the 90 second central mix (C-1) are poor, perhaps reflecting the short mixing time. The mixtures prepared with Mighty-150 at normal air contents show typically poor air-void characteristics for central-mix (MC-1) and ready-mix (RM-1) batches. Overlay mixtures, however, show excellent air-void characteristics. This further substantiates results obtained in utilization of the concrete mobile (see Section 7.1.3, Table 42); and indicates that a combination of high cement content and low SWR dosage level can offset the deterioration of the air-void system seen in other mixtures containing SWR.

The final set of results in Table 58 show the improvement in air-void characteristics brought about by increasing the

Use of higher air contents will result in some deterioration in strength values. Specimens were cast from Mixes RM-1, ROA-21, and ROA-31 for determination of compressive strength (ASTM C39-72) and modulus of rupture (ASTM C78-75). Compressive strength was determined at 1, 3, and 28 days of moist cure. Modulus of rupture was determined at 7 days of moist cure. Strength as a function of hardened air content is shown in Figure 53. At the level found to yield acceptable air-void systems (approximately 5% hardened air) strengths are reduced from 10-15% of the values at the lower, more typical air contents (approximately 4% hardened air).

To investigate the effects of high air contents on durability, specimens were cast from mixtures R-1, R-12, ROA-21, and ROA-31 for determination of deicer scaling resistance (ASTM C672-76). Testing

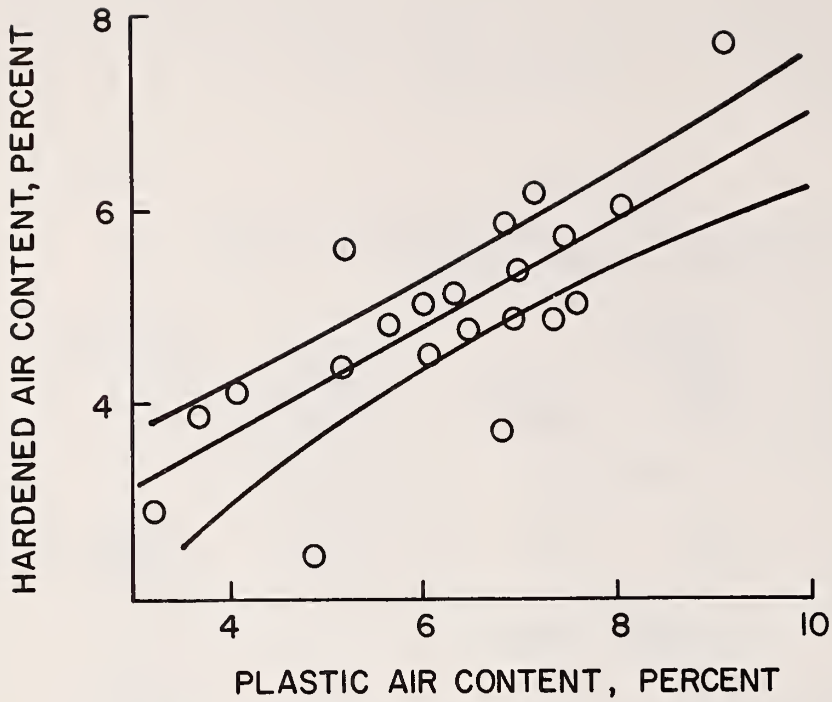

FIGURE 54 A. PLASTIC VERSUS HARDENED AIR CONTENTS

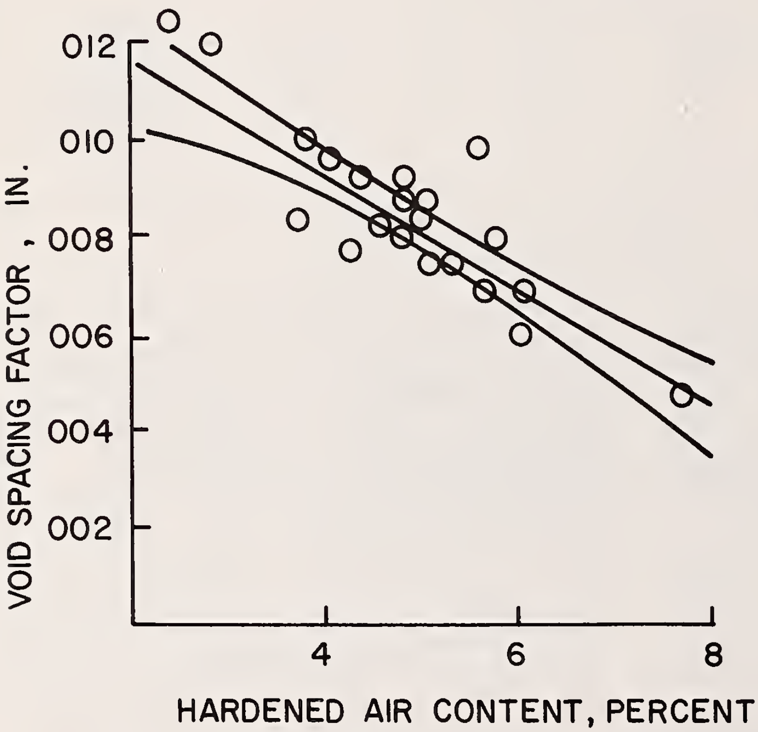

FIGURE 54 B. HARDENED AIR CONTENT VERSUS SPACING FACTOR

FIGURE 54. RELATIONSHIPS BETWEEN PROPERTIES OF AIR-ENTRAINED CONCRETES

was carried out to 300 cycles, results are shown in Table 59.

TABLE 59

Linear Traverse Results and Deicer Scaling Resistance of Concretes with Varying Air Contents

Mixture	Hardened Air Content (%)	Void Spacing Factor (in.) 1/	Scaling Rating 2/ 300 Cycles
R-1	4.1	0.0060	1
R-12	4.0	0.0084	4
ROA-21	6.0	0.0059	1
ROA-31	7.7	0.0047	0

1/ To convert from in. to mm multiply by 25.4.
2/ See ASTM C672-76.

Deicer scaling resistance is well-correlated with void spacing factor. For the mixture containing Mighty-150 at normal air content, void spacing factor is above the recommended limit of 0.008 in. (0.20 mm) and scaling is moderate to severe after 300 cycles of test. All the other mixtures exhibit void spacing factors less than 0.008 in. (0.20 mm) and very slight or no visible scaling. These tests indicate that concretes containing SWR must be designed so that hardened air contents are greater than about 5.0%. Based on results obtain in this series, this would imply the use of plastic air contents in the range of 7.0-8.0% for these concretes.

8.7 Air-Void Parameters for Concretes Prepared with Other SWR and A/E Agents at Various Air Contents

Data was needed on the air-void system developed in concretes prepared with combinations of other SWR and A/E agents. The two most commonly used air-entraining agent types are the Vinsol resins and sulfonated alkyl-benzene compounds. The two products chosen for this phase of the testing were neutralized Vinsol^R resin and Darex^R. The SWR chosen were Mighty-150, Melment L-10, and Alkanol. It should be noted that the latter is no longer available, and was an experimental product produced during the course of this project. Cement Lot No. 21802 (see Appendix D) was used for all mixtures.

The mixtures were designed using the "Ready-Mix" mix design previously described. As before the "delayed-addition" mode was used. That is, the A/E agent was added to the initial 3 minute mix, and the SWR was added after a 20 minute rest period. Specimens were cast for determination of air-void system characteristics both immediately after mixing the SWR into the batch and after 40 minutes.

Admixtures dosage levels and characteristics of fresh concretes are shown in Table 60. Also included are data on Mixtures RM-1A, ROA-2 and and ROA-3 as these were included in the data analysis. The final letter in the mix code (B or C) refers to a specimen cast at 40 or 60 minutes after initial mixing.

Linear traverse results are given in Table 61. Some interesting trends can be ascertained from these data and the properties given in Table 60. First of all, high plastic air contents in the range of 7.0-8.0 percent generally result in hardened air contents in the range of 5.0-6.0 percent, although there are exceptions, for instance Mixtures DXM-1 (Mighty-150 + Darex) and VRL-1 (Melment + NVR). Secondly, in most cases spacing factors less than the recommended limit of 0.008 in. (0.20 mm) are associated with hardened air contents greater than 5.0 percent. The two exceptions to this rule are Mixtures VRL-1B (Melment + NVR) and NVA-1B (Alkanol + NVR). There appears to be evidence of complex SWR/A/E agent interaction which influences the air-void system. For instance, with Mighty-150 and Alkanol better air-void systems are obtained when NVR is used, but with Melment L-10 Darex^R yields better parameters.

In order to establish some tentative quantitative recommendations on air contents for SWR concretes, the entire set of data on plastic air content, hardened air content, and void spacing factor were subject to two separate linear regression analyses. In the first set (Figure 54A) hardened air content was correlated with plastic air content. In the second set (Figure 54B) hardened air content was correlated with void spacing factor. In the plots $\pm$95% confidence limits are included as curves on either side of the line of least squares. Figure 54B indicates that to achieve a void spacing factor of 0.008 in. (0.20 mm) or less, a hardened air content of at least 5.5% is needed. In order to achieve this hardened air content, a plastic air content of 8.3% is needed (at the $\pm$95% confidence limit). This analysis, of course, is on the conservative side and lumps together the combinations where low spacing factors are achieved at relatively low air contents along with those combinations which are less favorable. Also, the relationships may shift if other cements,

TABLE 60

Admixture Dosage Levels and Characteristics of Fresh Concrete

Various Combinations of SWR and A/E Agents

Mix	SWR	Dosage (% s/c)	A/E Agent	Dosage (ml/lb) 1/	Slump (in.) 2/	Plastic Air Content (%)
RM-1A	Mighty-150	0.46	NVR	9.8	6.0	6.1
RM-14B	Mighty-150	0.46	NVR	9.8	1.1	3.7
ROA-2	Mighty-150	0.46	NVR	12.4	5.9	8.1
ROA-2B	Mighty-150	0.46	NVR	9.8	1.5	5.6
ROA-3	Mighty-150	0.46	NVR	16.6	5.8	9.2
ROA-3B	Mighty-150	0.46	NVR	9.8	3.2	6.9
AR-1	Alkanol	0.51	NVR	11.5	5.7	6.3
VRM-1	Mighty-150	0.46	NVR	11.3	5.8	7.0
VRM-1B	Mighty-150	0.46	NVR	11.3	2.9	6.5
DXM-1	Mighty-150	0.46	Darex	10.2	6.0	7.4
VRL-1	Melment L-10	0.55	NVR	22.1	5.1	7.0
VRL-1B	Melment L-10	0.55	NVR	22.1	0.9	5.2
DXL-1	Melment L-10	0.55	Darex	7.5	7.2	7.5
DXL-1B	Melment L-10	0.55	Darex	7.5	5.0	3.2
VL10-A1	Melment L-10A	0.55	NVR	17.6	6.0	6.1
VL10-A2	Melment L-10A	0.55	NVR	19.7	5.5	6.9
NVA-1	Alkanol	0.51	NVR	18.9	6.7	7.2
NVA-1B	Alkanol	0.51	NVR	18.9	2.0	5.2
NVA-1C	Alkanol	0.51	NVR	18.9	0.7	4.1
DXA-1A	Alkanol	0.51	Darex	8.8	6.8	7.6
DXA-1B	Alkanol	0.51	Darex	8.8	2.4	4.9

1/ To convert from ml/lb to ml/kg multiply by 2.20.
2/ To convert from in. to mm multiply by 25.4.

TABLE 61

Air Content And Air-Void Characteristics

Various Combinations of SWR and A/E Agents

Mix	SWR	A/E Agent	Plastic Air Content (%)	Hardened Air Content (%)	Voids per inch 1/	Specific Surface ($in.^2/in.^3$) 2/	Void Spacing Factor (in.) 3/
RM-1A	Mighty-150	NVR	6.1	5.0	6.9	551	0.0086
RM-1B	Mighty-150	NVR	3.7	3.8	5.1	541	0.0099
ROA-2	Mighty-150	NVR	8.1	6.0	10.8	715	0.0059
ROA-2B	Mighty-150	NVR	5.6	4.8	7.1	594	0.0081
ROA-3	Mighty-150	NVR	9.2	7.7	13.1	675	0.0047
ROA-3B	Mighty-150	NVR	6.9	5.8	8.1	558	0.0079
AR-1	Alkanol	NVR	6.3	5.1	8.1	638	0.0074
VRM-1	Mighty-150	NVR	7.0	5.3	8.3	619	0.0074
VRM-1B	Mighty-150	NVR	6.5	4.7	7.0	586	0.0082
DXM-1	Mighty-150	Darex	7.4	4.8	6.3	526	0.0091
VRL-1	Melment L-10	NVR	7.0	4.8	6.7	549	0.0087
VRL-1B	Melment L-10	NVR	5.2	5.6	6.5	463	0.0097
DXL-1	Melment L-10	Darex	7.5	5.7	9.2	642	0.0069
DXL-1B	Melment L-10	Darex	3.2	2.9	3.7	512	0.0120
VL10-A1	Melment L-10	NVR	6.1	4.4	6.1	551	0.0091
VL10-A2	Melment L-10	NVR	6.9	3.7	6.1	656	0.0083
NVA-1	Alkanol	NVR	7.2	6.1	9.3	613	0.0069
NVA-1B	Alkanol	NVR	5.2	4.3	7.0	656	0.0077
NVA-1C	Alkanol	NVR	4.1	4.1	5.6	544	0.0095
DXA-1A	Alkanol	Darex	7.6	5.0	7.1	569	0.0083
DXA-1B	Alkanol	Darex	4.9	2.4	3.2	534	0.0124

1/ To convert from voids per inch to voids per mm multiply by 0.0394.

2/ To convert from $in.^2/in.^3$ to mm^2/mm^3 multiply by 0.0394.

3/ To convert from in. to mm multiply by 25.4.

concrete mixtures, or admixtures are employed. The analysis does indicate that plastic air contents in SWR concretes must be about 2 percent higher than normally recommended for a given aggregate size.

9. Physical Properties of Concretes Containing SWR

The physical properties of concretes prepared with SWR have been well documented in a number of publications (8,9,25,26). For the most part, these publications deal with concretes prepared at the recommended dosages of SWR, moderate slump levels, and normal air contents. As the studies done under the present program indicated higher dosages, slumps, and air contents to be necessary in order to maintain workability and suitable air-void systems, it was deemed necessary to investigate the effects of these parameters on a large range of physical properties. The properties investigated are listed below:

1. Shrinkage upon set.
2. Compressive strength at 1, 7, 14, 28, 90, and 365 days.
3. Flexural strength at 7, 14, 28, 90, and 365 days.
4. Tensile strength at 7, 14, 28, 90, and 365 days.
5. Drying shrinkage.
6. Elastic Moduli at 28, 90, and 365 days.
7. Abrasion resistance.
8. Fatigue strength.
9. Volume change upon wetting and drying.
10. Coefficient of thermal expansion.
11. Creep.
12. Resistance to freeze-thaw cycling.
13. Resistance to deicer scaling.
14. Resistance to sulfate attack.
15. Resistance to D-cracking.
16. Chloride permeability and potential for reinforcing steel corrosion.

Various combinations of mix designs, cements, aggregates, and SWR were used for these tests. Materials, mix designs, and properties of fresh concretes are given in Appendix E. The reader is urged to review this material before proceeding further in the text.

9.1 Description of Test Methods

Most of the tests were carried out in accordance with standard ASTM, or Corps of Engineers techniques. Specimen type, conditioning, and any deviations from standard test procedures are described below.

9.1.1 Test 1 - Shrinkage Upon Set

The test used to determine shrinkage upon set (or "subsidence"), was developed at the Portland Cement Association and reported in an earlier publication (27). Concrete is cast into 12x12x6-in. deep (305x305x152 mm) waterproof wooden molds and consolidated by rodding. The surface is struck off by use of a wood float. An indicator consisting of an acrylic plastic disk approximately 5/8-in. (16 mm) in diameter and 1/16-in. (1.6 mm) thick is placed on the surface at the center of the slab. The indicator consists of a fine glass fiber about 1-in. (25 mm) long cemented to the center of the disk. The tip of the glass fiber is dipped in black ink. A cathetometer (Model M908, Gaertner Scientific Company), readable to the nearest 0.05 mm, is focused on the tip of the glass fiber. The first (zero) reading is taken 2 minutes after finishing the slab. During exposure, readings are taken at frequent intervals until subsidence stabilizes.

9.1.2 Test 2 - Compressive strength

Concrete was cast into 6x12-in. (152x 305 mm) watertight steel cylinder molds and consolidated by rodding. Specimens were cured under wet burlap overnight then transferred to a moist room maintained at $73 \pm 3^{o}F$ ($23 \pm 1.7^{o}C$) until the desired test age of 1, 7, 14 or 28 days. The remaining cylinders were then placed in a laboratory atmosphere maintained at $73 \pm 3^{o}F$ ($23 \pm 1.7^{o}C$) and $50 \pm 5\%$ RH, then tested at 90 and 365 days in accordance with ASTM C39-72.

9.1.3 Test 3 - Flexural Strength

For each batch, concrete was cast into 6x6x30-in. (152x152x762 mm) watertight steel beam molds and consolidated by rodding. Specimens were cured under wet burlap overnight, then placed in a moist room, maintained at $73 \pm 3^{o}F$ ($23 \pm 1.7^{o}C$) until the desired test age of 7, 14, or 28 days and then tested in accordance with ASTM C78-75. Two breaks were obtained on each beam tested. After 28 days of moist curing the remaining beams

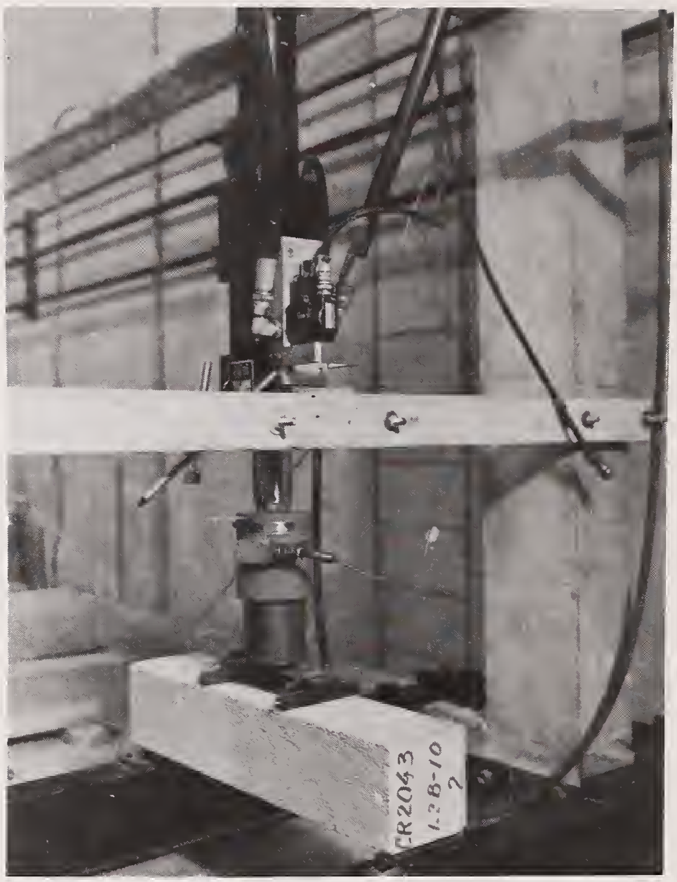

FIGURE 55. FATIGUE TEST APPARATUS

were placed in a laboratory atmosphere maintained at 73 ± 2°F (23 ± 1.7°C) and 50 ± 5% RH, then tested at ages of 90 and 365 days.

9.1.4 Test 4 - Tensile (Splitting) Strength

Concretes were cast into 6x12-in. (152x305 mm) steel cylinder molds and consolidated by rodding. The specimens were cured overnight under wet burlap, then stored in the moist room until the desired test age. They were then tested in accordance with ASTM C496-71 after 7, 14, and 28 days at moist storage. The remaining cylinders were then placed in a laboratory atmosphere for air drying, then tested at ages of 90 and 365 days.

9.1.5 Test 5 - Drying Shrinkage

Concretes were cast into 3x3x11.25-in. (76x76x286 mm) prisms molds fitted with stainless steel gage studs as specified in ASTM C490-77. They were cured under wet burlap overnight, then transferred to a moist room maintained at 73 ± 3°F (23 ± 1.7°C) for a period of 28 days. They were then removed from the moist room and initial readings were taken on a length comparator. The specimens were placed in laboratory air maintained under the drying conditions specified by ASTM C157-75. Readings were taken on the length comparator after 4, 7, 14, 28, 56, 112, 224, and 448 days of drying.

9.1.6 Test 6 - Elastic Moduli

9.1.6.1 Compressive Modulus

Specimens (previously described in Section 9.1.2) to be tested for compressive strength were tested in accordance with ASTM C469-65 prior to obtaining ultimate strength. An unbonded compressometer utilizing calibrated linear variable differential transformers was used to measure longitudinal strain. No measurements of transverse strain were made. After the stress-strain curves in the elastic region had been obtained the yoke was removed and the ultimate compressive strength was determined.

9.1.6.2 Flexural Modulus - Dynamic

Specimens (previously described in Section 9.1.3) to be tested for flexural strength were weighed at 90 days and their fundamental transverse resonant frequencies were determined in accordance with ASTM C215-60. Dynamic Young's modulus of elasticity was then computed from the fundamental frequency of vibration, weight, and specimen dimensions as prescribed. The dynamic modulus can be taken as an approximation to the static flexural tangent modulus at infinitesimally small strain.

9.1.7 Test 7 - Abrasion Resistance

Concretes were cast into 12x12x3-in. deep (305x305x76 mm) waterproof wooden molds. They were struck-off with a wood screed and finished with a magnesium float. They were cured under burlap overnight, then placed in a moist room maintained at 73 ± 3°F (23 ± 1.7°C) for 28 days and transferred to laboratory air maintained at 73 ± 3°F (23 ± 1.7°C) and a relative humidity of 50 ± 5% until time of test. Due to difficulties with test equipment, actual tests were carried out at 130 days of age rather than 90 days as originally planned. Testing was done in accordance with ASTM C779-76 (Procedure B - Dressing Wheels).

9.1.8 Test 8 - Fatigue Strength

Concretes were cast as 6x6x30-in. (152x152x762 mm) beam specimens and cured under wet burlap overnight. They were then transferred to a moist room maintained at 73 ± 3°F (23 ± 1.7°C) for a period of 28 days. They were then placed in air maintained at 73 ± 3°F (23 ± 1.7°C) and 50 ± 5% RH. Originally, beams were scheduled to be tested after 90 days in air, however, difficulties with equipment lead to a postponement of the testing. At the initiation of testing the beams had been in air for approximately 230 days. Testing was conducted over a 3 month period.

Fatigue testing was carried out on a closed-loop electro-hydraulic dynamic testing system (MTS Systems Corporation, Minneapolis, Minnesota), see Figure 55. Beams were tested on a 28-in. (710 mm) span in third-point loading. The loading cycles consisted of a 6 Hz sinusoidal load having a minimum value of 25 psi and a maximum between 50 and 80 percent of the static flexural strength, depending upon the particular specimen being tested. Testing on each specimen was carried out until failure, or until 2 X 10^6 cycles had been completed.

Because the age at test was significantly greater than 90-days, and since fatigue tests generally exhibited large specimen-to-specimen variations, calculations of the percentage stress applied in fatigue if based on the 90-day data would necessarily be inexact. To obtain more accurate data, portions of the beams tested to failure in fatigue were tested statically on 12-in. (305 mm) spans. Beams tested in fatigue but not exhibiting failure ("run-out" at 2 X 10^6 cycles), were tested statically in third-point loading on 28-in. (711 mm) spans,

then the portions retested on 12-in. (305 mm) spans. The averages of these latter two data sets for controls and admixture specimen groupings were then used to derive correction factors which could be used to correct all the 12-in. (305 mm) span data to a value representing a 28-in. (711 mm) span. The ratio of 12-in. (305 mm) to 28-in. (711 mm) span data typically ranges from 0.95 to 0.96 (28).

9.1.9 Test 9 - Volume Change Upon Wetting and Drying

Concretes were cast into 3x3x11.25-in. (76x76x286 mm) prism molds fitted with stanless steel gage studs as specified in ASTM C490-77. They were cured under wet burlap overnight, then transferred to a moist room maintained at 73 ± 3°F (23 ± 1.7°C) for a period of 28 days. Initial length readings were taken at this time. The specimens were then placed in air maintained at 73 ± 3°F (23 ± 1.7°C) and a relative humidity of 50 ± 5% for a period of 4 days and remeasured. The specimens were then placed in the moist room for an additional 10 days and remeasured. The 4-day air - 10-day moist cycle was continued for a period of 1 year.

9.1.10 Coefficient of Thermal Expansion

Prisms identical to those used in Test 9 were cured in a moist room for 28 days. They were then tested in accordance with CRD-C39-55. In essence, this involves measurement of length after equilibration under water at 140°F (60°C) and 40°F (4.4°C). The value is thus the average coefficient of thermal expansion over this temperature interval.

Companion prisms were removed from the moist room at 28 days of age and placed in air at 73 ± 3°F (23 ± 1.7°C) and a relative humidity of 50 ± 5% for a period of 6 months. Specimens were then wrapped in successive layers of plastic sheeting and aluminum foil so as to restrict moisture loss. They were then heated to 100°F (37.8°C) for 6 hours and length measurements were taken. They were then placed at 40°F (4.4°C) overnight and remeasured. Coefficient of thermal expansions reported are thus an average over this temperature range.

9.1.11 Test 11 - Creep

Duplicate 6x12-in. (152x305 mm) cylindrical specimens were cast into steel molds and cured under burlap overnight. They were then transferred to a moist room maintained at 73 ± 3°F (23 ± 1.7°C) for a period of 28 days. They were then transferred to air at 73 ± 3°F (23 ± 1.7°C) and a relative humidity of 50 ± 5% for a period of 21 days. Length readings were then taken over a 10-in. (25 mm) gage length on all specimens. Specimens were then placed in loading frames and loaded to 2,500 psi (17.2 MPa). This represents 40% of the 28-day compressive strength for the controls and 30% of the 28-day compressive strength for the specimens prepared with Mighty-150. Testing was then carried out in accordance with ASTM C512-76. Specific creep (in millionths per psi-MPa) was first calculated, subtracting initial elastic strain and drying shrinkage from the measured values. Specific creep was then normalized by multiplying by the 28-day compressive strength.

9.1.12 Test 12 - Resistance to Freeze-Thaw Cycling

Concrete specimens were cast as 3x3x 11.25-in. (76x76x286 mm) prisms fitted with stainless steel gage studs as specified in ASTM C490-77. They were cured under wet burlap overnight, then transferred to a saturated lime-water solution maintained at 73 ± 3°F (23 ± 1.7°C) for a period of 14 days. They were then measured for initial weight, length and fundamental transverse frequency of vibration, then placed under test.

The test equipment (Logan Freezing and Thawing Apparatus, Logan Refrigeration Company, Logan, Utah) meets the requirements of ASTM C666-77, Procedure A.

Specimens are placed into copper containers 3.25x12x3.5-in. deep (83x305x89 mm). A 0.125-in. (3 mm) wire is placed at the bottom of the container. Plastic spacer blocks are placed at both ends of the cointainer so that 0.125-in. (3 mm) of water surrounds the specimen on all sides. The freeze-thaw cycle consists of a 2.5-hour freeze from +43°F (+6.1°C) to -3°F (-19.4°C) followed by a 1.0 hour thaw from -3°F (-19.4°C) to +43°F (+6.1°C). This allows for approximately 6.5 freeze-thaw cycles per 24-hour period. The test is continued up to 300 cycles. Length, weight, and fundamental transverse frequency of vibration are measured at frequent intervals, approximately every 40 cycles.

9.1.13 Test 13 - Resistance to Deicer Scaling

Concretes are cast into 6x15x3-in. deep (152x381x76 mm) molds and given a wood float finish. They are then allowed to set for approximately 6 hours at which time the periphery of the specimen faces are scored and a mortar dike approximately 0.5-in. (13 mm) wide is cast onto

the surface of the specimens. This produces a test area of approximately 60 in.^{2} (0.039 m^2). The specimens are then stored under wet burlap overnight, then transferred to a moist room for 28 days. At this time the surface of the specimen is covered with a 4% solution of calcium chloride, and the specimens are transferred to a walk-in freezer maintained at 0 ± 3°F (-17.8 ± 1.7°C) for a period of 16 to 18 hours. They are then transferred to air maintained at 73 ± 3°F (23 ± 1.7°C) for a period of 6 to 8 hours. Slabs are flushed clean and new solution is added every 7 cycles. This procedure is essentially that of ASTM C672-76, with the exception of a smaller test area and a longer conditioning time prior to initiation of test. The smaller test area has not been shown to be a problem with this procedure, and the longer conditioning time was chosen so as to achieve a higher degree of saturation in the specimens prior to test. Scale ratings, using the system described in ASTM C672-76 are made after 5, 10, 15, 25, and every 25 cycles thereafter. The test is continued out to 300 cycles or until the specimen exhibits a scale rating of 5 (severe scaling).

9.1.14 Test 14 - Resistance to Sulfate Attack

Concretes were cast into 3x3x11.25-in. (76x 76x286 mm) prism molds fitted with stainless steel gage studs as specified in ASTM C490-77. They were cured under burlap overnight, then transferred to a moist room maintained at 73 ± 3°F (23 ± 1.7°C) for a period of 14 days. They were then placed in air at 73 ± 3°F (23 ± 1.7°C) and a relative humidity of 50 ± 5% for an additional 14 days. The purpose of the air-drying period was to increase the saturation potential of the concrete prisms prior to immersion in the sulfate solution.

After the air-drying period had elapsed the prisms were measured for initial length, weight, and fundamental transverse frequency of vibration. They were then placed in a solution of 10% sodium sulfate by weight and stored at 73 ± 3°F (23 ± 1.7°C) for 16 hours overnight. They were then placed in a high temperature room maintained at 130 ± 3°F (54.4 ± 1.7°C) for 8 hours. This cycle was repeated daily. Measurements of length change, weight, and fundamental transverse frequency of vibration were made after 1, 2, 4, and 8 weeks of test and every 4 weeks thereafter up to 52 weeks. This procedure is similar to the accelerated sulfate test procedure used by the Bureau of Reclamation (29), with the exception of the concentration of sodium sulfate being higher in the present test.

9.1.15 Test 15 - Resistance to D-Cracking

The test specimens, equipment, and procedure for this test are identical to that used in Test 12 (Resistance to Freeze-Thaw Cycling). A failure criteria of 0.035% or greater expansion at 350 cycles has been recommended by the Ohio Department of Transportation.

9.1.16 Test 16 - Chloride Permeability and Potential for Reinforcing Steel Corrosion

Concretes from each mixture were cast into duplicate 12x12x6-in. deep (305x305x 152 mm) waterproof wooden molds. For each concrete cast one of the molds contained a mat of reinforcing steel consisting of three transverse and two longitudinal No. 4 (12.7 mm) reinforcing bars spaced on 5-in. (127 mm) transverse centers and 8-in. (203 mm) longitudinal centers. Clear cover over the transverse steel was 0.5-in. (13 mm). Concrete was consolidated by external vibration using a vibrating table. Mortar dikes similar to those used for the deicing slabs (see 9.1.13) were cast onto the surfaces of the specimens after initial set. Companion slabs without reinforcement (but with dikes) were also prepared.

The specimens were stored under moist burlap overnight, then transferred to a moist room maintained at 73 ± 3°F (23 ± 1.7°C) for 28 days. At the end of this time period the half-cell potential of the reinforcing steel at 3 locations on the surface of the slabs were determined. Potentials were obtained on a high impedance voltmeter (Fluke Model 8020A) between a copper/copper sulfate (CSE) half-cell electrode placed on the surface of the concrete and a stainless steel pin snug-fitted into the end of a rebar prior to casting. After all initial potential readings had been obtained the slabs were placed in a drying room maintained at 73 ± 3°F (23 ± 1.7°C) and a relative humidity of 50 ± 5% for two days, at which time an epoxy coating was applied to the four sides of each slab. After 10 days in air a 3.0% sodium chloride solution was applied to the surface of each slab for 4 days, the solution was then flushed off and half-cell potentials (CSE) were redetermined. The slab was then allowed to air-dry for an additional 10 days. The 4-day pond, 10-day dry cycle was continued for a period of 1 year (26 cycles). Half-cell (CSE) potentials were determined at the end of every 4-day ponding period.

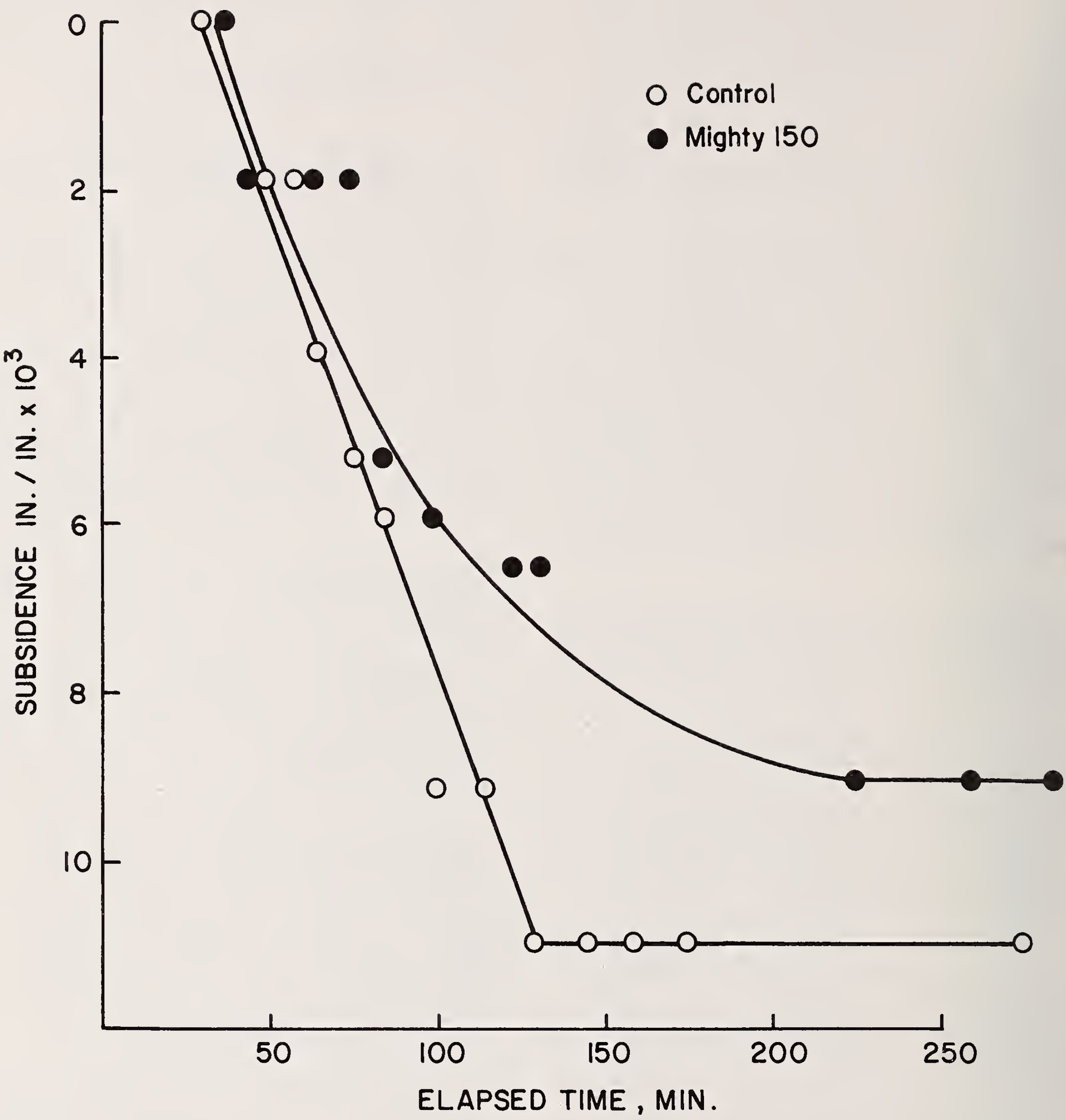

FIGURE 56. SUBSIDENCE OF FRESH CONCRETES DURING SETTING PERIOD

TABLE 62

Compressive Strength Versus Time

No.[1]	SWR	Compressive Strength,[2] psi[3] at Age Indicated, Days (% of Control) 1	7	14	28	To Air	90	365
1.1	None	2,470	4,960	5,780	6,330		7,830	7,640
2.1	Mighty-150	4,130	6,720	7,290	7,950		9,540	9,700
		(167)	(135)	(126)	(126)		(122)	(127)
3.1	Melment L-10	4,790	7,080	7,290	8,240		9,100	9,320
		(194)	(143)	(126)	(130)		(116)	(122)

1/ Refer to Tables 93-94, Appendix E for mix designs and characteristics.
2/ Average of triplicate specimens.
3/ To convert from psi to MPa multiply by 0.0069.

TABLE 63

Flexural Strength Versus Time

No.[1]	SWR	Flexual Strength,[2] psi[3] at Age Indicated, Days (% of Control) 7	14	28	To Air	90	365
1.2	None	790	850	920		790	1,105
2.2	Mighty-150	990	1,090	1,150		890	1,070
		(125)	(128)	(125)		(113)	(97)
3.1	Melment L-10	1,050	1,030	1,140		920	1,170
		(133)	(121)	(124)		(116)	(106)

1/ Refer to Tables 93-94, Appendix E.
2/ Average of two tests each on duplicate beams.
3/ To convert from psi to MPa multiply by 0.0069.

TABLE 64

Tensile Strength Versus Time

No.[1]	SWR	Tensile Strength,[2] psi[3] at Age Indicated, Days (% of Control) 7	14	28	90	365
1.1	None	480	525	495	575	556
2.1	Mighty-150	485	510	570	590	560
		(101)	(97)	(115)	(103)	(101)
3.1	Melment L-10	570	575	610	570	660
		(119)	(110)	(123)	(99)	(119)

1/ Refer to Tables 93-94, Appendix E.
2/ Average of triplicate specimens.
3/ To convert from psi to MPa multiply by 0.0069.

TABLE 65

Drying Shrinkage of Concretes

No.[1]	SWR	Drying Shrinkage,[2] percent at Age Indicated, Weeks (% of Control) 1	2	4	8	16	32	64
1.1	None	0.017	0.024	0.031	0.037	0.038	0.041	0.042
2.1	Mighty-150	0.017	0.025	0.030	0.037	0.039	0.038	0.043

1/ Refer to Tables 93-94, Appendix E
2/ Average of triplicate specimens

After the end of drying cycles Nos. 1, 5, 15, and 26, samples for analysis of total chloride content were obtained from the non-reinforced slabs using an electric rotary hammer tool (Phillips Roto-Stop Hammer Model 747). Samples were obtained at depth increments of 0 to 0.25 in. (0 to 6 mm), 0.25 to 0.50 in. (6 to 13 mm), 0.75 to 1.0 in. (19 to 25 mm), and 1.5 to 1.75 in. (38 to 44 mm), using a 1.125-in. (28 mm) diameter carbide drill bit. Powdered samples were analyzed for total chloride using the equipment and technique (Grans' Plot Titration) recommended by FHWA (30). Sample holes were backfilled with epoxy after removal of all of the sample.

9.2 Test Results

9.2.1 Test 1 - Shrinkage Upon Set

Test results are plotted in Figure 56 as subsidence (in mm/mm X 10^{-3}) versus time elapsed after start of mixing. Although the rates of settlement are similar within the first hour, after this the water reduced concretes exhibit progressively less settlement with time and level off at a value of 9 X 10^{-3} after 225 minutes. The controls level off at a somewhat higher value (11 X 10^{-3}) after 125 minutes. Therefore, we may say that settlement continues for longer time periods in concretes containing Mighty-150, but the absolute magnitude of the shrinkage is less.

9.2.2 Test 2 - Compressive Strength

Compressive strength as a function of time for controls and mixtures containing SWR is shown in Table 62. Strength increases lie within the ranges seen in other investigations on super-water reducers (9,25). Early-age strengths are excellent, approaching 5,000 psi (34.5 MPa) for the Melment L-10 mix at 1 day. At later ages the strength difference between control and SWR mixtures decreases, to approximately 20% at 90 days and 25% at 365 days.

9.2.3 Test 3 - Flexural Strength

Results for flexural strength are shown in Table 63. Values up to 28 days represent moist-curing conditions, values at 90 and 365 days represent air-cured specimens. Flexural strength gain (as a percentage of control values) is somewhat less than for compressive strength at 7 days, and approximately equal at 7 and 14 days. Drop in strength between 28 and 90 days can be attributed to the air-storage period, which apparently induces tensile stresses on the outer beam fibers due to drying shrinkage. Strength again increases between 90 and 365 days of age, although 1-year strengths are essentially equal for control and SWR concretes.

9.2.4 Test 4 - Tensile (Splitting) Strength

Split tensile strengths are shown in Table 64. Results are not as clearly defined as those for compressive or flexural strengths. This may be attributed to the higher amount of scatter in splitting tensile tests.

9.2.5 Test 5 - Drying Shrinkage

Data on comparative drying shrinkage of controls and water-reduced specimens containing Mighty-150 are given in Table 65. There is essentially no difference between control and water-reduced specimens.

9.2.6 Test 6 - Elastic Moduli

Values of compressive moduli at 28, 90, and 365 days, and flexural moduli at 90 days are given in Table 66 for control and Mighty-150 concretes.

TABLE 66

Elastic Moduli of Concretes

No.1/	SWR	Compressive Modulus,2/ psi3/ X 10^6 at Age Indicated, Days: 28	90	365
1.1	None	4.77	5.05	4.83
2.1	Mighty-150	5.13	5.77	5.23

No.1/	SWR	Flexural Modulus,2/ psi X 10^6 at Age Indicated, Days: 90
1.1	None	6.02
2.1	Mighty-150	6.42

1/ Refer to Tables 93-94, Appendix E
2/ Average of triplicate specimens
3/ To convert from psi to MPa multiply by 0.0069.

Moduli of water-reduced concretes are increased approximately 10 percent over that of controls at equal age. Values for compressive moduli are within 4 percent of values calculated from

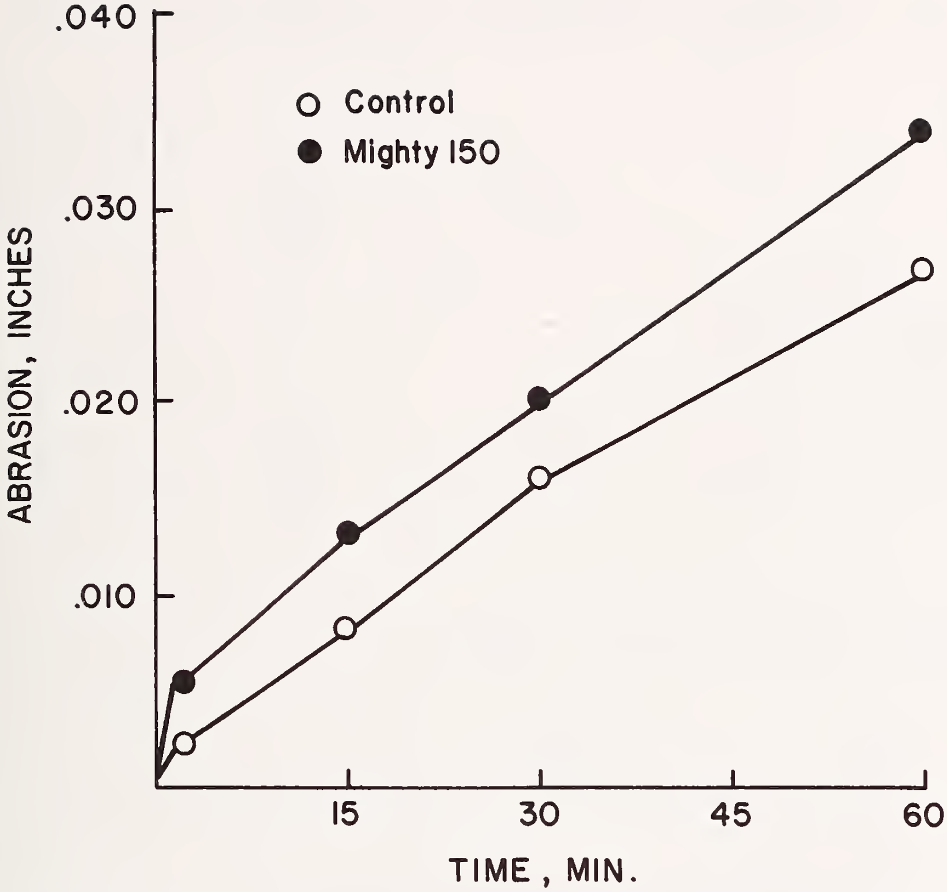

FIGURE 57. ABRASION OF CONCRETE SLABS USING DRESSING WHEELS

TABLE 67

Static Flexural Strengths on 12-Inch[1/] and 28-Inch Load Spans and Computed Ratios

Specimen	Admixture	Measured Flexural Strength, psi[2/] 12-inch Span	28-inch Span	Ratio 12 inch/28 inch	Corrected[3/] 28-inch Strength
1.2 A-8-1	None	737			877
1.2 A-8-2	None	856			1,019
1.2 A-8-3	None	772			919
1.2 A-8-4	None	722			860
1.2 B-8-1	None	767	985	0.78	913
1.2 B-8-2	None		1,024	0.88	1,071
1.2 B-8-3	None		1,035	0.86	1,064
			Average	0.84	
2.2 A-8-1	Mighty-150	983			1,129
2.2 A-8-2	Mighty-150	972			1,117
2.2 A-8-3	Mighty-150	978			1,124
2.2 A-8-4	Mighty-150	833			957
2.2 B-8-1	Mighty-150	922	1,059	0.87	1,060
2.2 B-8-2	Mighty-150	1,028	1,155	0.89	1,182
2.2 B-8-3	Mighty-150	1,044	1,223	0.85	1,200
2.2 B-8-4	Mighty-150	1,006	1,171	0.86	1,156
			Average	0.87	

1/ To convert from in. to mm multiply by 25.4.
2/ To convert from psi to MPa multiply by 0.0069.
3/ Corrected strength = measured strength   Ratio.

TABLE 68

Fatigue Test Results for Concrete Specimens

Specimen	Admixture	Applied Fatigue Stress (psi)[1/]	Static Flexural Strength (psi)[2/]	Stress/Strength Ratio	Cycles to Failure
1.2 A-8-1	None	514	877	0.59	3/
1.2 A-8-2	None	514	1,019	0.50	4/
1.2 A-8-3	None	593	919	0.65	654,000
1.2 A-8-4	None	632	860	0.73	1,500
1.2 B-8-1	None	593	913	0.65	4/
1.2 B-8-2	None	616	1,071	0.58	4/
1.2 B-8-3	None	616	1,064	0.58	4/
2.2 A-8-1	Mighty-150	578	1,129	0.51	4/
2.2 A-8-2	Mighty-150	668	1,117	0.60	4/
2.2 A-8-3	Mighty-150	712	1,124	0.63	500,300
2.2 A-8-4	Mighty-150	757	957	0.79	1,800
2.2 B-8-1	Mighty-150	729	1,060	0.69	2,000
2.2 B-8-2	Mighty-150	712	1,182	0.60	4/
2.2 B-8-3	Mighty-150	757	1,200	0.63	4/
2.2 B-8-4	Mighty-150	757	1,156	0.65	4/

1/ To convert from psi to MPa multiply by 0.0069.
2/ Corrected to 28-in. (711 mm) loading span.
3/ Testing machine failure.
4/ Run-out (no failure at 2 X 10^6 cycles).

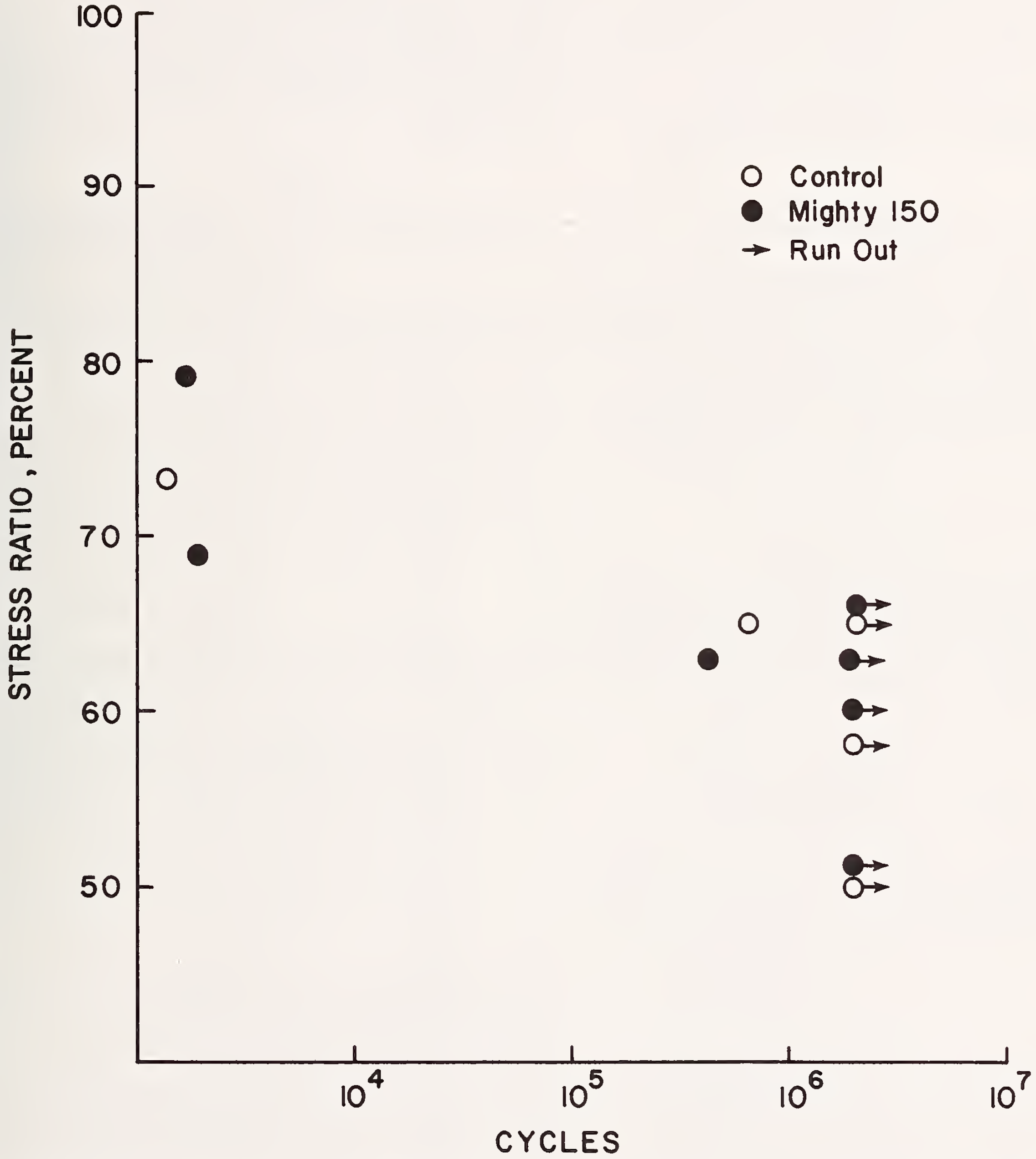

FIGURE 58. S-N CURVE FOR CONCRETES SUBJECT TO FLEXURAL FATIGUE

compressive strength using an empirical equation specified in ACI 318-77.[1/]

$$E_c = W_c^{1.5} \bullet 33 \sqrt{f'_c} \qquad (2)$$

where: E_c = modulus of elasticity (psi)

W_c = unit weight (lb/ft^3)

f'_c = compressive strength (psi)

Moduli of elasticity in flexure are 11 percent and 19 percent higher than corresponding compressive moduli for controls and Mighty-150 specimens. This can be attributed to the use of the dynamic technique for determination of the modulus, which yields essentially a tangent modulus at zero strain, versus the average secant modulus determined in compression.

9.2.7 Test 7 - Abrasion Resistance

Surface abrasion during the 60-minute tests on control and Mighty-150 specimens is plotted in Figure 57. During the initial few minutes of test the Mighty-150 specimens exhibited a higher rate of abrasion than the controls. The rates are essentially the same for the duration of the test. Total abrasion of the Mighty-150 slabs is 25 percent greater than for controls.

9.2.8 Test 8 - Fatigue Strength

Static flexural strength data taken from portions of beams tested in fatigue are given in Table 67. The last column shows the "corrected" 28-in. (711 mm) span flexural strength data, obtained by dividing by the average of the ratio of 12-in. (305 mm) to 28-in. (711 mm) strengths obtained on "run-out" beams. The static flexural strengths shown in Table 68 are these corrected values. Also shown in Table 68 are the ratio of applied fatigue stress during test to the static (computed) flexural strength of the beam under test. About 65 percent of the specimens did not exhibit failure at the chosen end-point of 2×10^6 cycles. These are termed "run-out" specimens.

The S-N curve for the two data sets is shown in Figure 58. Although the data are typical for what one might expect for plain concrete (31), the scatter makes it difficult to ascertain whether there is any significant difference between the fatigue behavior of the control and Mighty-150 specimens. This is not surprising, as the statistical nature of fatigue can often result in variations in fatigue life as high as 100:1 within a single data set (32). Although these problems can be overcome by use of statistical techniques, the number of specimens needed to develop accurate statistics was beyond the scope of the present program.

9.2.9 Test 9 - Volume Change Upon Wetting and Drying

Length readings taken after each 10-day wet and 4-day dry period indicate little significant changes after the initial cycle. Controls exhibit somewhat lower levels of overall change after the eighth cycle. Within any given cycle, however, the Mighty-150 specimens exhibit less of a change between the wet and dry periods. Data taken every fourth cycle are given in Table 69.

TABLE 69

Volume Change Upon Wetting and Drying

Cycle	Condition	Volume Change - Percent: Control	Difference
4	Dry	-0.037	0.026
4	Wet	-0.011	
8	Dry	-0.029	0.014
8	Wet	-0.015	
12	Dry	-0.028	0.017
12	Wet	-0.011	
16	Dry	-0.026	0.015
16	Wet	-0.011	
20	Dry	-0.026	0.015
20	Wet	-0.011	
24	Dry	-0.027	0.015
24	Wet	-0.012	

Cycle	Condition	Volume Change - Percent: Mighty-150	Difference
4	Dry	-0.033	0.021
4	Wet	-0.012	
8	Dry	-0.029	0.018
8	Wet	-0.011	
12	Dry	-0.030	0.012
12	Wet	-0.018	
16	Dry	-0.028	0.012
16	Wet	-0.016	
20	Dry	-0.027	0.010
20	Wet	-0.017	
24	Dry	-0.034	0.012
24	Wet	-0.022	

9.2.10 Test 10 - Coefficient of Thermal Expansion

Coefficients of thermal expansion (CTE) determined in the moist condition at 28

1/ ACI 318-77 "Building Code Requirements for Reinforced Concrete," Section 8.5.

days, and after 6 months of air drying are given in Table 70.

TABLE 70

Coefficients of Thermal Expansion

SWR	Coefficient of Thermal Expansion (in./in./^{o}F)1/ Moist - 28 Day	Air-Dry 6 Months
None	5.97	6.98
Mighty-150	5.59	6.87

1/ To convert from in./in./^{o}F to m/m/^{o}C multiply by 1.8.

In the moist condition CTE for Mighty-150 specimens are 7 percent lower than for controls. In the air-dry condition they are only 2 percent lower. Air dry results are about 16 percent higher than moist values for controls and 23 percent higher than moist values for Mighty-150 specimens. This is as expected, as CTE of concrete is highest at intermediate moisture contents and lowest in the dry or saturated conditions (33).

9.2.11 Test 11 - Creep

As both control and Mighty-150 specimens were loaded to the same stress level of 2,500 psi (17.2 MPa), control cylinders were exposed to a higher stress relative to the ultimate strength than were Mighty-150 cylinders. To correct for this, specific creep data (10^{-6}/psi - 10^{-6}/MPa) have been multiplied by the 28-day strength in order to obtain a non-dimensional quantity termed "Normalized Creep". This procedure has been suggested by Neville (34).

Plots of normalized creep versus time under load are almost identical for the two sets of specimens (Figure 59). These data indicate that if Mighty-150 is used to increase working stress levels, there will be essentially no change in creep response at the higher stress levels as compared to a normal-strength concrete under lower loads.

9.2.12 Test 12 - Resistance to Freeze-Thaw Cycling

All concretes exhibited little deterioration in freeze-thaw cycling. Results showing percent expansion, weight loss, and relative dynamic modulus at 300 cycles are listed in Table 71.

TABLE 71

Results of Freeze-Thaw Testing at 300 Cycles

Cement Lot No.	SWR	Relative Dynamic Modulus	Percent Expansion	Percent Weight Loss
21817	None	94.5	0.020	4.2
	Mighty-150	95.5	0.030	0.9
21818	None	94.1	0.019	2.3
	Mighty-150	96.2	0.028	1.6

Some surface scaling was noted in the control specimens beginning at about 80 cycles. This is reflected in the higher weight loss of control specimens. Specimens containing Mighty-150 appear to have dilated somewhat more than controls. These levels of expansion, however, (approximately 0.03%) are below the levels of 0.05-0.10% generally used to indicate failure in testing where expansive mechanisms of damage are known to be operative.

9.2.13 Resistance to Deicer Scaling

Results of deicer scaling tests were very interesting. Concretes containing the SWR performed poorly as compared to controls. Data in Table 72 indicate progressive deterioration of these specimens beginning at about 50 cycles.

TABLE 72

Deicer Scaling Tests

Cement Lot No.	SWR	Scale Rating1/ at Cycle Indicated 25	50	100	175	250	300
21817	None	0	0	1	1	1	1
	Mighty-150	1	2	2	3	4	4
	Melment L-10	1	1	2	3	4	5
21818	None	0	0	0	0	0	0
	Mighty-150	1	2	2	3	3	3
	Melment L-10	1	2	3	4	4	5

1/ Scale Ratings: 0 = no scaling
1 = slight scaling
2 = slight to moderate scaling
3 = moderate scaling
4 = moderate to severe scaling
5 = severe scaling.

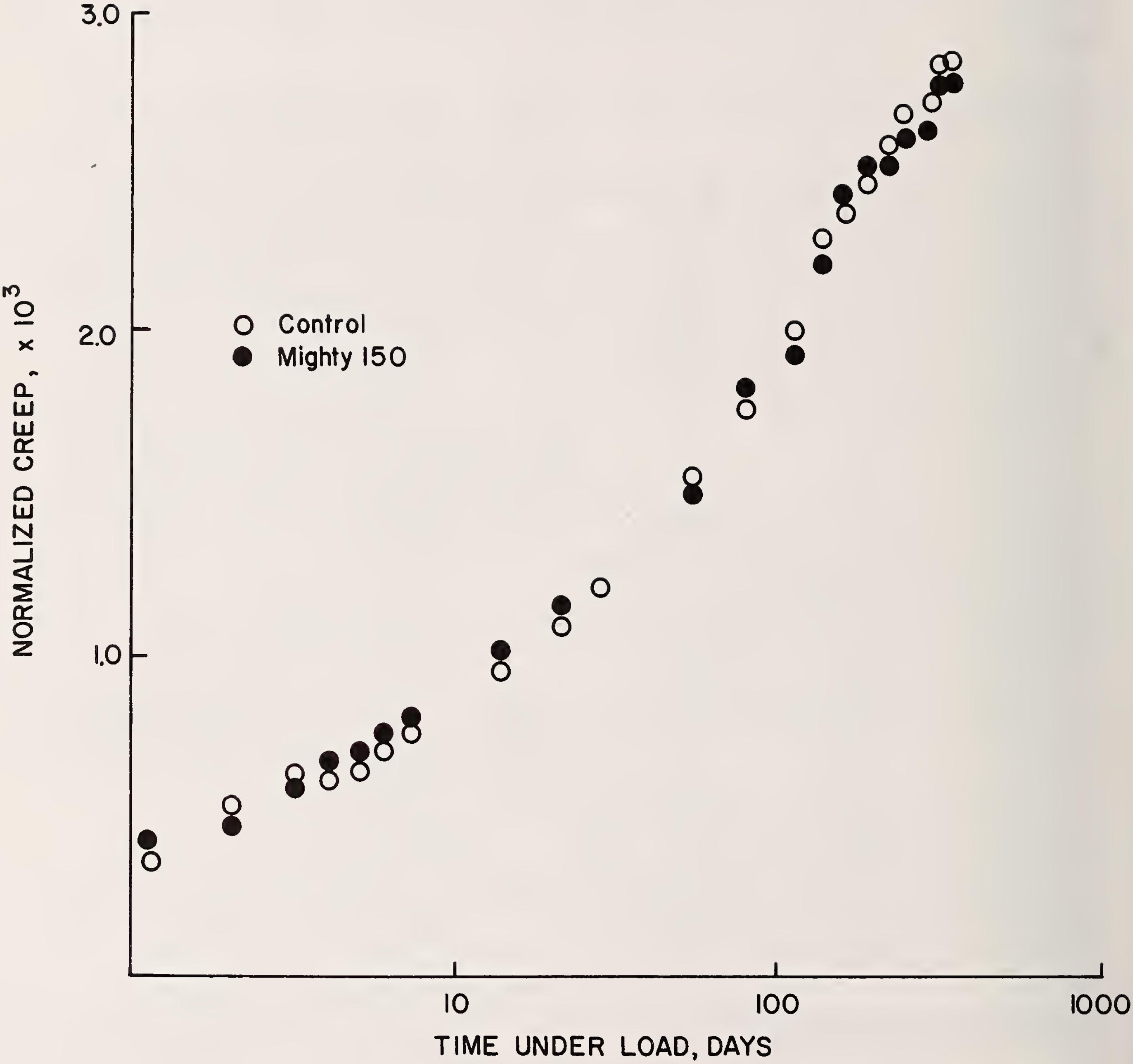

FIGURE 59. NORMALIZED CREEP AS A FUNCTION OF TIME

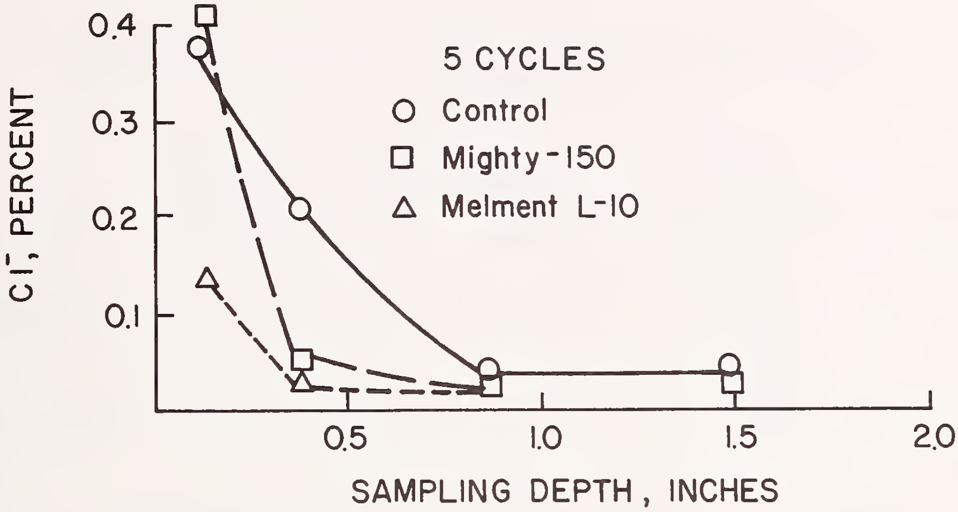

FIGURE 60A. CHLORIDE PROFILES AT 5 CYCLES

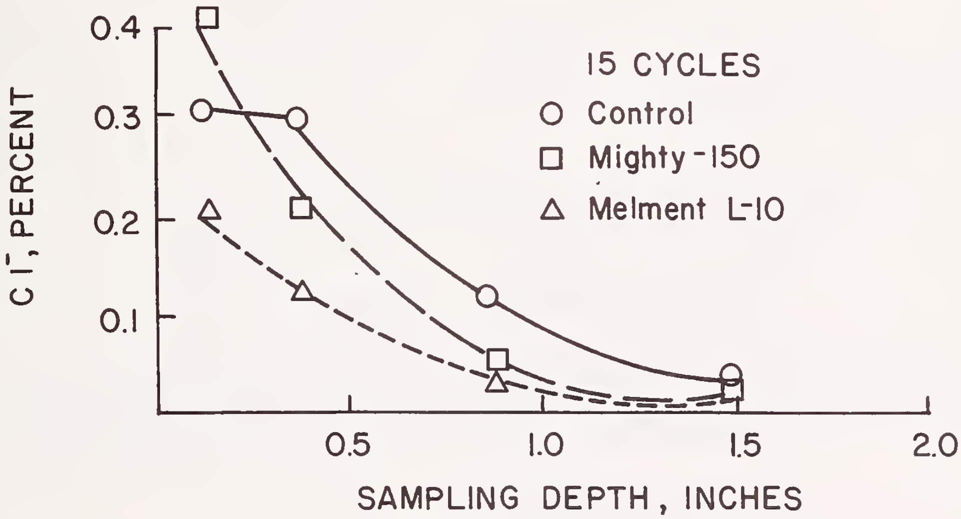

FIGURE 60B. CHLORIDE PROFILES AT 15 CYCLES

FIGURE 60. CHLORIDE PROFILES AT VARIOUS CYCLES

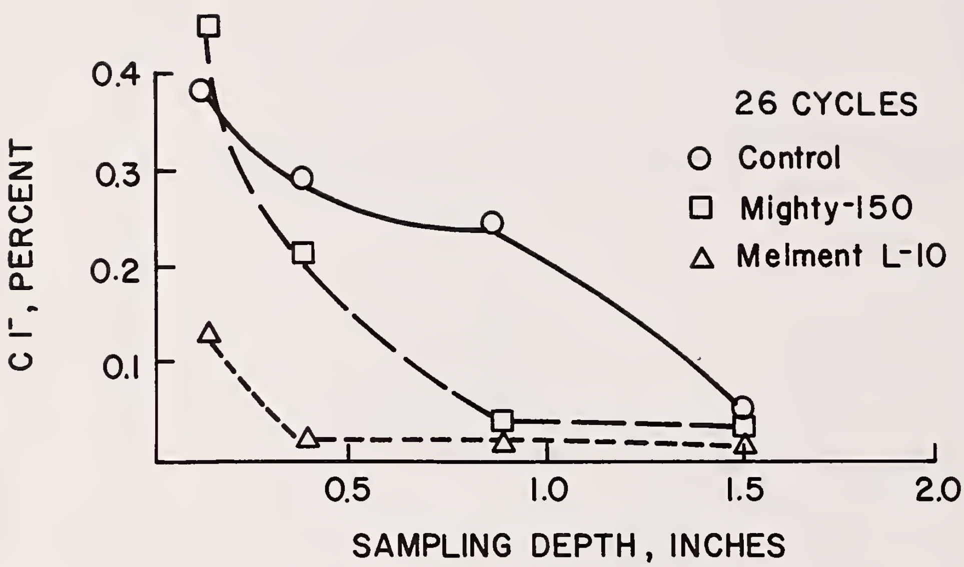

FIGURE 60C. CHLORIDE PROFILES AT 26 CYCLES

FIGURE 60 (CON'T). CHLORIDE PROFILES AT VARIOUS CYCLES

This deterioration may perhaps be explained by results of linear traverse analyses conducted on concrete specimens cast from these mixtures at the same time that the scaling specimens were made. The data in Table 73 show all concretes containing SWR to exhibit relatively low specific surface and high spacing factors. The spacing factor data show an excellent correlation with scale ratings at 300 cycles. These high spacing factors can be attributed to the loss of initial air contents in the plastic state. Earlier work (see Section 8.7) had shown that it was necessary to achieve hardened air contents greater than 5 percent in order to obtain acceptable spacing factors (0.008 in. (0.20 mm), in concretes containing SWR. In the previous cases, plastic air contents from 7-8 percent were sufficient to achieve this hardened air level. Apparently, a complex SWR/Cement/A/E agent interaction exists which influences the amount of air lost between the initial (plastic) and final (hardened) states.

TABLE 73

Air Content and Air-Void Characteristics of Concretes

Cement Lot No.	SWR	Plastic Air Content (%)	Hardened Air Content (%)	Voids per inch 1/	Specific Surface (in.^{2}/in.^{3}) 2/	Spacing Factor (in.) 3/
21817	None	6.2	3.8	10.1	1,061	0.0054
	Mighty-150	8.0	4.3	5.2	475	0.0106
	Melment L-10	7.8	4.5	4.8	426	0.0118
21818	None	6.5	5.0	12.8	1,028	0.0048
	Mighty-150	7.4	4.3	6.6	617	0.0082
	Melment L-10	7.1	3.9	5.5	557	0.0096

1/ To convert from voids per inch to voids per mm multiply by 0.0394.

2/ To convert from in.^{2}/in.^{3} to mm^2/mm^3 multiply by 0.0394.

3/ To convert from in. to mm multiply by 25.4.

9.2.14 Test 14 - Resistance to Sulfate Attack

For cement of moderate (approximately 8%) C_3A content, such as No. 21817, only minor improvements in sulfate resistance are made through the use of either Mighty-150 or a Class F fly ash (Table 74). This is not unexpected, due to the high cement factor (658 lb/yd^3 - 390 kg/m^3) and relatively low water-cement ratio of the control mixture. It is only in high C_3A cements (less than 10%) especially susceptible to sulfate attack, where either the lower water-cement ratio afforded by the SWR or the pozzolanic activity afforded by the fly ash can be used to advantage in such cement-rich mixtures.

This is not to say, however, that SWR cannot be an effective means of improving sulfate resistance of lower quality concretes. This might be especially true in areas where high-quality Class F fly ash is not available.

9.2.15 Test 15 - Resistance to D-Cracking

Although the phenomenon of "D-cracking" is primarily controlled by properties of the coarse aggregate (35), it was felt that the increased strength and reduced permeability of concretes containing SWR might reduce the severity of damage in concretes produced with aggregates prone to this problem.

The results (Table 75) indicate that although the reduced water-cement ratio of the concrete containing Mighty-150 does retard the progress of deterioration, the limit of 0.035% expansion after 350 freeze-thaw cycles established by Ohio DOT is still exceeded.

9.2.16 Test 16 - Chloride Permeability and Potential for Reinforcing Steel Corrosion

Chloride profiles (as percent Cl^- by weight of samples versus mean sampling depth) are shown in Figures 60 A-C for 5, 15, and 26 cycles, respectively. With the exception of the first samples

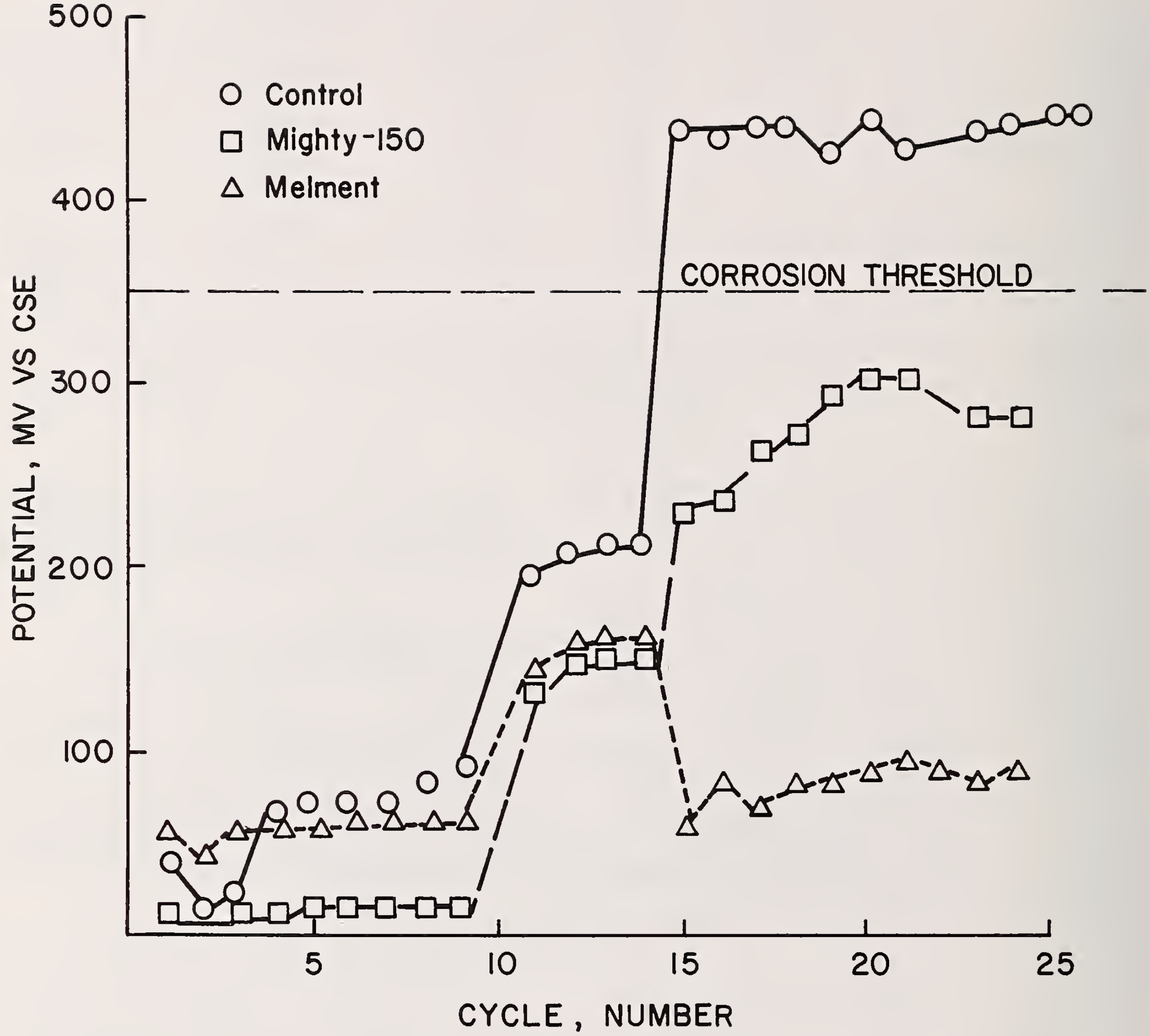

FIGURE 61. VARIATION OF COPPER/COPPER SULFATE POTENTIALS DURING CYCLING

TABLE 74

Results of Sulfate Testing

52 Weeks of Test

Cement Lot No.	SWR	Class F Fly Ash	Percent Weight Change	Percent Expansion	Relative Dynamic Modulus
21817	None	None	+0.92	0.060	110
	Mighty-150	None	+0.46	0.047	110
	None	Yes	+0.50	0.033	109
LTS-18	None	None	-1.68	0.637	62
	Mighty-150	None	-1.14	0.039	111
	None	Yes	+0.66	0.048	113
LTS-51	None	None	+0.37	0.031	115

TABLE 75

Results of Freeze-Thaw Testing in Concretes Containing Aggregate Susceptible to D-Cracking

	Percent Expansion After Cycle Indicated							
SWR	25	59	85	143	200	260	300	351
None	0.003	0	0.006	0.017	0.030	0.041	0.070	0.080
Mighty-150	0.002	0.001	0.004	0.011	0.018	0.023	0.048	0.057

at 0 to 0.25 in. (0 to 6 mm), the indicated permeability is in the order:

Control > Mighty-150 > Melment

As the steel has only 0.5-in. (13 mm) of clear cover, sufficient chloride to initiate corrosion has migrated to the vicinity of the steel within 5 cycles of test.

Potentials (Figure 61) show an upward trend between 5 and 10 cycles of test, then appear to level off between 10 and 15 cycles. At 15 cycles the control specimens exceed the corrosion threshold of -350 mv versus CSE. Mighty-150 specimens exhibit potentials near -300 mv versus CSE, within the region of uncertainty as to whether corrosion is actively occurring (36). Melment L-10 specimens showed a jump in potential from -60 mv to -150 mv versus CSE at 10 cycles, but potential dropped back again to -60 mv at 15 cycles and remained below -100 mv for the remainder of the testing. All Melment L-10 potentials were within the region where a high probability of no corrosion is indicated.

10. Guide to the Use of Super-Water Reducers for Highway Applications

10.1 Introduction

This guide is intended as a supplement to the more extensive data reported in previous sections. Its aim is to acquaint the potential user of super-water reducers with the properties of these admixtures and techniques for optimizing their effectiveness for highway applications. This section can be read without having thoroughly studied the main text of the report, however, the text should be used as a reference where indicated.

Some of the information presented in this guide is based on manufacturers' literature, reports from testing agencies, personal communications, and published data.

The author has attempted to interpret this information in light of the results of this study, however, due to time and budget limitations many suggested procedures especially field techniques, could not be verified. The user of this guide should be aware that this information may be unsubstantiated.

10.2 General Information on Super-Water Reducers

Super-water reducers (SWR) are chemical admixtures falling mainly into two basic classes, naphthalene and melamine formaldehyde condensation products. Detailed descriptions and chemical analyses can be found in Section 2 of the main text. They are usually supplied in liquid form, although powdered versions of FX-32 and Lomar-D are available. The stated half life of these products range from 6 months to "unlimited". A usable life of 1 year storage at ambient temperature is recommended.

Costs (1977) range from \$1.70/gal (\$0.45/liter) to \$5.70/gal (\$1.51/liter). Based on typical dosage levels used in the present study (i.e., dosages needed to achieve a water-cement ratio of 0.35 or less with a cement content of 658 lb/yd^3 (390 kg/m^3)), add-on costs of these products to a cubic yard of concrete could range from \$2.20/yd^3 (\$2.88/m^3) to \$3.30/yd^3 (\$4.32/m^3) for a typical naphthalene-based product.

These products are recommended for use at dosages of 10-20 fl oz/bag of cement (6.9-18.8 ml/kg) for the more concentrated naphthalene products and 20-40 fl/oz bag (13.8-27.7 ml/kg) for the more dilute melamine product. The actual dosage needed for a particular job will be a function of the particular cement used, mix design (expecially cement factor), water-cement ratio desired, temperature, type of mixer, addition time of admixture, and other variables. More specific guidelines on dosage rates will be given later in this manual.

The user is strongly urged to ensure that all concrete has been thoroughly mixed for a period not less than 3 minutes prior to introduction of the SWR. It is further recommended that the elapsed time between start of initial mixing and time of addition of SWR be not less than 6 minutes. In addition to improvement in mix homogeniety, delay in addition improves the effectiveness of the admixture and may allow one to obtain increased workability at the same dosage or reduce dosage and realize a cost savings at the specified slump. If haul times greater than 20 minutes are anticipated addition of SWR should be delayed until the unit has reached the jobsite. Delay in addition of SWR of up to 60 minutes after mixing can be tolerated with little loss of effectiveness. Small dosages of SWR can be added in addition to the original dose in order to maintain constant workability. The total dosage added <u>should never</u> exceed 1.0% by weight of cement on a solids basis. This is equivalent to 28 fl oz per bag (19.4 ml/kg) of cement for Mighty-150 and 61 fl oz per bag (42.2 ml/kg) of cement for Melment L-10. <u>In no case should transportation in non-agitating units be attempted</u>. Slump loss can be severe with these products, especially in mixtures of moderate cement content designed for water-cement ratios less than 0.35.

No major changes in concrete mix designs (other than reduction in water-cement ratio) need be made when using SWR. A small increase in sand content (approximately 5%) may be useful to avoid a "rocky" mix. If desired, total paste content may be increased to compensate for the volume of water removed from the batch. This may be done by use of additional cement, fly ash or other finely ground materials. The water-cement ratio should be maintained, however.

In mixes typical of those used for full-depth pavement and bridge deck construction having cement contents of 560-660 lb/yd^3 (330-390 kg/m^3) SWR can be used to reduce water-cement ratios to less than 0.35. In order to maintain sufficient workability over the time period envisioned for transport and placement, however, initial design slumps should be in the range of 5-6 in. (127-152 mm). This slump should be obtained by increasing the dosage of SWR, <u>not</u> by increasing water content. In no case, however, should dosage of SWR exceed 1.0% solid admixture by weight of cement, and at levels between 0.6% and 1.0% laboratory tests to varify effect on setting time and early strength development should be made. Air contents should be increased into the range of 7-8%. The type and addition sequence of A/E agent does not have as much of an effect as the actual air content used. Even at relatively high air contents, however, certain combinations of materials may result in rapid loss of air from the plastic concrete. Once again, laboratory tests should be carried out with job materials prior to initiation of full-scale production.

Concretes containing SWR can be placed using conventional techniques. Highly fluid mixtures, which will be typical of the material initially discharged from a R/M truck, can be placed with a minimum of vibration. If no additional SWR is added the final discharge may begin to exhibit slump loss, depending upon the particular cement, admixture, and temperature, among other factors. In this case use of a large amplitude, high acceleration (greater than 100 g - 981 m/s^2) type internal vibrator may be of benefit for ease in placement.

10.3 Qualification of Super-Water Reducers

These products are generally available from reputable manufacturers of concrete admixtures. Table 76 lists currently (1980) available SWR and their suppliers. It should be noted that formulations are constantly changing and new products are being introduced. The user should ensure that the products meet the requirements of ASTM C494-80 (Standard Specification for Chemical Admixtures for Concrete) prior to purchase.

Specifications included in 1980 ASTM standards are given in Table 77.

Most manufacturers supply detailed product sheets describing the current usage of their products. Information generally included concerns availability, color, dosage rate, and some guidelines as to use in specific applications. The extent of detail varies considerably with the manufacturer.

The dosages quoted in manufacturers literature generally vary over quite a wide range. In a later section a more exact method of determining a starting dosage rate will be presented. In order to use this method the specific gravity and solids content of the liquid admixture must be known. This is not generally available in the literature received from the manufacturer although technical representatives may be queried as to this data. Additionally, the information presented in Table 3 of this report may be used. On products not tested in this report the user may desire to obtain his own results. Techniques for determination of these two properties are presented.

10.3.1 Determination of Specific Gravity

Specific gravity is determined in accordance with ASTM C494-79 Section 18.4. A water bath maintained at 25 $\pm$ 1°C is not necessary, as three significant figures (i.e., $\pm$ 0.01 unit) are adequate for mix design purposes.

10.3.2 Determination of Solids Content

Solids content is determined in accordance with ASTM C494-79, Section 18.2 (Residue by Oven-Drying). As determination to $\pm$ 0.1% is adequate for mix design purposes, the precision of weighing can be reduced to $\pm$ 0.01 gm.

10.4 Estimation of Dosage Requirements for Super-Water Reducers

The dosage rates recommended in manufacturers' tech sheets are meant to cover a wide range of concrete mixtures. The present study has been confined to mixtures typical of those used in highway applications, thus data developed can be used to establish more accurate guidelines as to required dosage rates of SWR.

The three basic mixtures covered in this study were a moderate cement content mixture (564 lb/yd^3 - 335 kg/m^3) typically used for full-depth paving jobs, a moderately high cement content mixture (658 lb/yd^3 - 390 kg/m^3) used in placement of full-depth bridge decks and other high-strength structures, and a very rich mixture (822 lb/yd^3 - 488 kg/m^3) used in placement of dense, impermeable concrete overlays. All mixtures are designed for a water-cement ratio of 0.35 or slighty below. In the paving and bridge deck mixtures it is recommended that the SWR be added at the jobsite, if at all possible. An initial slump of 5-6 in. is targeted. In the overlay mixture, where the use of a concrete mobile is recommended, the SWR is added during the initial mix cycle. An initial slump of 2-3 in. is targeted. The dosage recommendations given in this manual refer specifically to these addition sequences.

The dosage needed to obtain the recommended slumps can be obtained using three techniques. The first is a semi-quantitative method where the results of mill test certification of cement chemical analyses are used to judge the cement as requiring a low, moderate, or high dosage of SWR. The second is a method whereby an equation developed during the course of this study is used to compute the required dosage. The third requires actual determination of dosage rate by using a "mini-slump" test procedure.

10.4.1 Procedure 1 - Semi-Quantitative

This procedure can be used to obtain a starting dosage of SWR when mill test certificates for the job cement are available but no further cement tests are desired. These data are based on tests conducted with Mighty-150 (naphthalene class SWR) and Melment L-10 (melamine class SWR) with a large number of cements. The cement characteristics found to be most important in determining required dosage were C_3A content, Blaine fineness, and alkali content (as Na_2O). The required dosage of SWR will be proportional to these three characteristics. Recommended dosages of Mighty-150 and Melment L-10 for various levels of these three cement constituents are given in Table 78. These data are valid for air-entrained concretes having a cement content of 658 lb/yd^3 (390 kg/m^3), water-cement ratio of

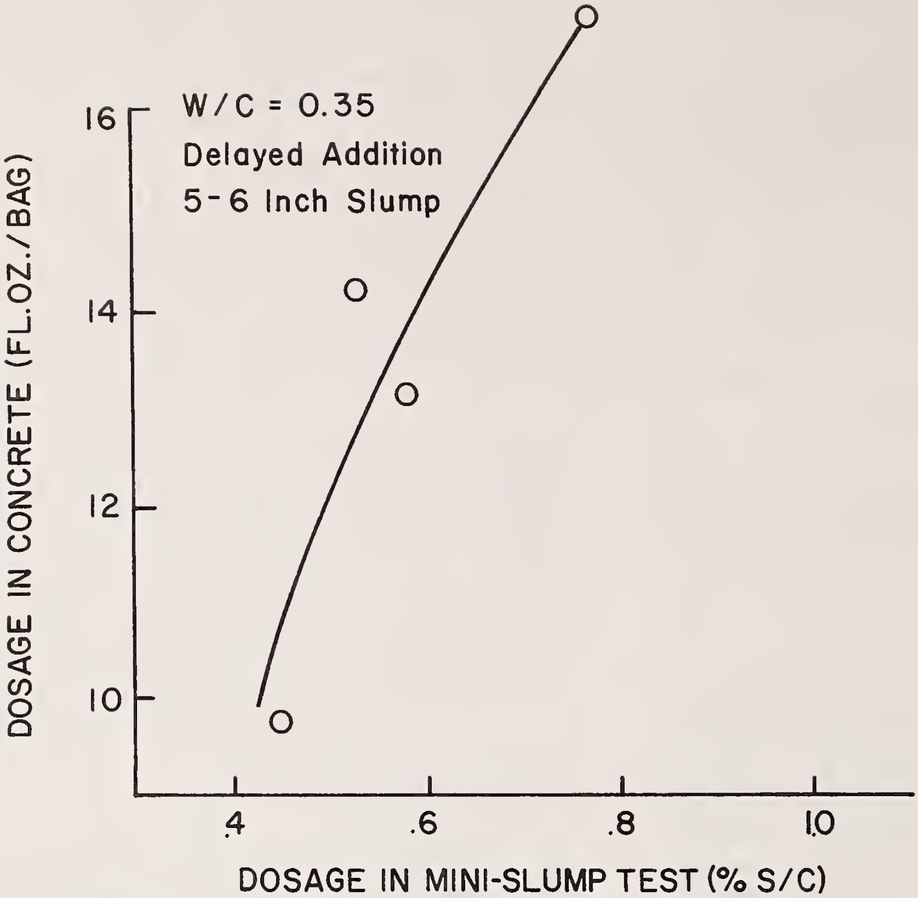

FIGURE 62A. CEMENT CONTENT 658 LB. PER CUBIC YARD

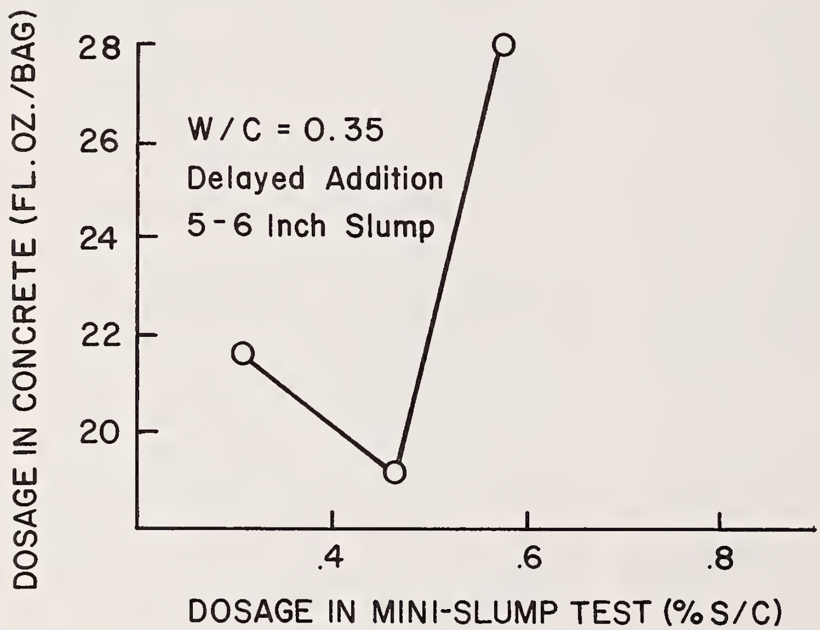

FIGURE 62B. CEMENT CONTENT 564 LB. PER CUBIC YARD

FIGURE 62. RELATIONSHIPS BETWEEN SWR DOSAGES OBTAINED IN MINI-SLUMP TEST AND IN CONCRETES

TABLE 76

Currently (1980) Available Super-Water Reducers and Their Suppliers

Product	Supplier	Address
Melment L-10 Melment L-10A	American Admixtures Corp.	5909 N. Rogers Ave. Chicago, IL 60646
Mighty-150 Mighty-150 RD2	ICI United States, Inc.	Wilmington, DE 19877
Lomar-D	Diamond Shamrock Corp.	P.O. Box 23^86R Morristown, NJ 07960
FX-32	Fox Industries	140 W. Mount Royal Ave. Baltimore, MD 21201
Sikament	Sika Chemical Corp.	Box 297 Lyndhurst, NJ 07071
WRDA-19	W. R. Grace and Company	62 Whittemore Ave. Cambridge, MA 02140
PSP-N	Protex Industries Inc.	1331 W. Evans Ave. Denver, CO 80223
PSP-R	Protex Industries Inc.	1331 W. Evans Ave. Denver, CO 80223
Mulcoplast CF	Mulco, Inc.	2835 Grande Allée St. Hubert (Que.) J4T 3K3

TABLE 77

1980 ASTM Specifications for Types F and G High-Range Water Reducers

	Type F Water Reducing - High Range	Type G Water Reducing - High Range and Retarding
Water Content, maximum, percent of control	88	88
Time of Setting, allowable deviation from control, hr:min		
Initial: at least	--	1:00 later
not more than	1:00 earlier nor 1:30 later	3:30 later
Final: at least	--	--
not more than	1:00 earlier nor 1:30 later	3:30 later
Compressive Strength, minimum, percent of control:		
1 day	140	125
3 days	125	125
7 days	115	115
28 days	110	110
6 months	100	100
1 year	100	100
Flexural Strength, minimum, percent of control:		
3 days	110	110
7 days	100	100
28 days	100	100
Length Change, maximum shrinkage (alternative requirements):		
Percent of control	135	135
Increase over control	0.010	0.010
Relative Durability Factor, minimum	80	80

0.35, a temperature of 70-75°F (21-24°C), and use of SWR in the delayed addition mode.

TABLE 78

Estimation of SWR Dosage Requirement from Mill Test Data

Blaine Fineness (cm^2/g)	C_3A (%)	Alkali- as Na_2O (%)	Dosage-fl oz/bag Mighty-150	Dosage-fl oz/bag Melment L-10
3200	<6	<0.5	<10	<28
3200 - 3800	6-9	0.5-0.7	10-13	28-36
3800	>9	>0.7	13-17	36-46

1/ To convert from fl oz/bag to ml/kg multiply by 0.692.

For any other SWR, if their generic class is known the required dosage can be computed from the following equation.

$$D_A = \frac{SG_M \bullet S_M}{SG_A \bullet S_A} \times D_M \qquad (3)$$

where: D = required dosage of given SWR (in fl oz/bag)

D_M = required dosage of Mighty-150 or Melment L-10 (in fl oz/bag)

SG_M = specific gravity of Mighty-150 or Melment L-10

S_M = solids content of Mighty-150 or Melment L-10

SG_A = specific gravity of given SWR

S_A = solids content of given SWR

10.4.2 Procedure 2 - Calculation

Results of the mini-slump testing used in this investigation allowed the development of an equation relating dosage rate in cement paste to the alkali content, C_3A content, and Blaine fineness of the cement. Use of this equation requires the determination of C_3A content via x-ray diffraction techniques. Good correlations suitable for quantitative work were obtained only for Mighty-150. Therefore, this method can be used exactly only for this one SWR. The required dosage for other SWR of the naphthalene class can be obtained by calculating the amount of Mighty-150 and then obtaining the dosage of the SWR in question by use of Equation 3. The required dosage for Melment L-10 can be estimated by multiplying the value obtained for Mighty-150 (in fl oz/bag) by 2.80.

The following equation is used to determine the dosage of Mighty-150 needed for 30% water reduction in cement paste.

$$D_M = -.472 + 2.078 \times 10^{-4}B + .065C - .037A \qquad (4)$$

where: D_M = required dosage of Mighty-150 (% s/c)

B = Blaine fineness (cm^2/g)

C = C_3A content (via x-ray dif-diffraction) - %

A = alkali content (as Na_2O - %)

Once the dosage of Mighty-150 (% s/c) is obtained, Figure 62 is used to determine the required dosage in concrete (fl oz/bag). Note that significantly higher dosages are needed for concretes having a lower cement content.

10.4.3 Procedure 3 - Use of Mini-Slump Technique

The dosage of Mighty-150 required for 30% water reduction in cement paste can be directly determined through the mini-slump procedure described in Appendix B. On smaller jobs the cost of set-up and training of personnel in the use of the procedure will not be justified. However, the user should consider this procedure as a valuable quality control tool for larger construction projects, as it will allow one to detect potential problems in cement/SWR compatibility. For instance, if extremely high dosage requirements are indicated, the user may wish to switch cement sources prior to initiation of full-scale concreting operations. Conversely, the user may sample a number of cement sources prior to initiation of the project, and select the one exhibiting the lowest SWR dosage requirement. Finally, the test may be used on a daily basis in order to sample cement shipments and detect any variations which may require changes in dosage.

10.5 Effect of Cement Content

Super-water reducers become more effective as cement content is increased. This effect is manifested in two ways. At a fixed dosage of SWR, higher water reductions are possible in richer mixtures. At a fixed water-cement ratio, less SWR will be required to achieve this ratio in a richer mixture. The

dosage requirements presented in the previous sections were based on mixtures with a cement content of 658 lb/yd^3 (390 kg/m^3). Richer mixtures than this would probably be used only in dense overlay applications. Leaner mixtures would be more typical of various other highway applications. Suggested dosage rates of Mighty-150 and Melment L-10 in mixtures having cement contents of 822 lb/yd^3 (488 kg/m^3) and 564 lb/yd^3 (335 kg/m^3) are given in Table 79 in terms of a correction factor which can be used to obtain the dosage once the dosage for a 638 lb/yd^3 (390 kg/m^3) mixture has been arrived at using one of the three recommended techniques.

TABLE 79

Correction Factors for Determining Dosage at Cement Contents Typically Used in Highway Applications

Cement Content (lb/yd^3) 2/	Typical Application	Slump (in.) 3/	Correction Factor 1/
828	Dense Overlay	2-3	0.3
564	Full Depth Pavement	5-6	2.0

1/ First determine dosage for 658 lb/yd^3 mixture. Then multiply by this correction factor to obtain dosage for other mixtures.
2/ To convert from lb/yd^3 to kg/m^3 multiply by 0.594.
3/ To convert from in. to mm multiply by 25.4.

In many cases the specified slump will not be obtained on the first trial mixture. The large number of mixtures prepared during the course of this study have allowed the preparation of some guidelines as to dosages necessary to charge slump by 1-in. which should be helpful in obtaining the target slump with the least number of trial mixtures. These are shown in Table 80.

TABLE 80

Amount of Super-Water Reducer Needed to Change Slump by 1 inch 1/

Mix Description	Cement Content (lb/yd^3) 2/	Dosage of Super-Water Reducer (fl oz/bag) 3/ Mighty-150	Melment L-10
Bridge Deck Mix[4]	658	0.75-1	3-6
Pavement Mix[5]	564	3-4.5	5-15
Overlay Mix[4]	823	0.5	2.5

1/ To convert from in. to mm multiply by 25.4.
2/ To convert from lb/yd^3 to kg/m^3 multiply by 0.5935.
3/ To convert from fl oz/bag to ml/kg multiply by 0.693.
4/ Super-water reducer added after 20 min delay.
5/ Super-water reducer added to mix water - 90 sec. total mix.

10.6 Effect of Temperature

Quantitative data concerning the effect of temperature on dosage requirements of SWR are limited. Results obtained in this study indicate that, when used in the delayed addition mode (i.e., addition of the SWR 20 minutes after mixing) more SWR is needed as the ambient temperature decreases. For every decrease of 1°F (0.55°C) below 75°F (23°C) approximately 1.2 fl oz/yd^3 (27 ml/m^3) of Mighty-150 or 2.6 fl oz/yd^3 (58 ml/m^3) of Melment L-10 would be needed to maintain constant initial slump. Above 75°F up to 90°F the dosage rate is little affected by temperature, provided that evaporation losses are kept to a minimum.

10.7 Mimimization of Slump Loss in Concretes Containing Super-Water Reducers

Slump loss is a complex phenomenon influenced by a number of variables. Among these influences are composition of the cement, cement content, water-cement ratio, admixture dosage, addition time, initial slump level, and temperature.

For a discussion of chemical influences the reader is referred to Section 3.3 of the main text, which deals with "pat area loss" studies on neat cement pastes. The main conclusions of these studies are

that cements having high values of C_3A, alkali, and fineness will show high levels of slump loss, although this does not hold true in every instance. Also, the pat area loss data is not directly translatable into concrete slump loss data. The paste tests are more sensitive than tests on corresponding concretes, thus higher rates of pat area loss in paste do not necessarily mean one will see a higher rate of slump loss in concrete. For these reasons, while judicious choice of a cement may allow one to reduce SWR dosage rate, cement chemical composition, within reasonable limits, cannot be used as a criteria for minimization of slump loss. The following guidelines, based mainly on mix design and production factors, will contribute more strongly to reduction of slump loss than will use of any particular cement. The following guidelines refer specifically to preparation of concretes having net water-cement ratios of 0.35 or less. The guidelines also assume that the concrete will have to be transported within typical time intervals (15-45 min) to the jobsite. These guidelines do not apply to operations where placement location is immediately adjacent to the mixer (such as precasting operations). In extreme cases, however, slump loss may be a factor in these instances also. Procedures specific to certain operations will be described in later sections.

1. At a fixed water-cement ratio (say 0.35 or less), the higher the cement content of the mix the lower the rate of slump loss will be. Slump loss will be especially severe in mixtures of moderate cement contents, large (1.5 in. (28 mm) or more) aggregate sizes, containing angular aggregate. In no case should one attempt to produce low water-cement ratio concrete from lean (less than 500 lb/yd^3 - 296 kg/m^3) concrete mixtures.

2. The more one attempts to reduce the water content, the higher the rate of slump loss will be. Mixtures exhibiting high water demands will be especially vunerable to slump loss if "pushed" to low water-cement ratios (w/c = 0.35 or less). The problem can be alleviated somewhat by an increase in paste (i.e., cement plus water) content at the fixed target water-cement ratio, however, this will increase cost of the concrete.

3. Slump should be specified at 5-6 in. (127-152 mm) at initial discharge. This slump should be obtained by varying the admixture dosage in trial mixtures, using the guidelines set forth in Section 10.3.

4. If at all possible, SWR should be added after the initial mixing period has been completed. If long transport times are anticipated, SWR should be added at the jobsite. <u>In no instance shall concretes containing SWR prepared at low water-cement ratios be transported in non-agitating units</u>. If concrete becomes unworkable during placement of a partial load, additional SWR can be added to the remainder of the load to restore workability.

5. Mixing and placement at elevated temperatures will aggrevate slump loss. Procedures recommended by ACI[1/] for hot-weather concreting should be adhered to. Chemical retarders may be used to reduce slump loss at elevated temperatures. Their use will be described in a later section.

10.8 <u>Use of Super-Water Reducers in Ready-Mixed Concrete Operations</u>

10.8.1 <u>Pre-Construction Procedures</u>

The performance of SWR in low water-cement ratio concrete is a complex function of admixture, cement composition, mix design, temperature, mix cycle, mixer type and other factors. To reduce the possibility of encountering severe problems during actual construction, preparation and testing of trial batches is strongly recommended. Trials should be run in two stages. Firstly, small batches should be prepared in the laboratory using the same materials which are to be used on the job. These batches can be used to obtain preliminary admixture (SWR and A/E agent) dosages and for determination of various important properties of the concrete. Although, obviously, one cannot conduct a research program every time SWR are to be used, the following properties should be evaluated every time a new material, batching or mixing procedure is introduced.

1. Dosage of SWR necessary to achieve desired slump.

1/ ACI 305R-77 "Hot Weather Concreting".

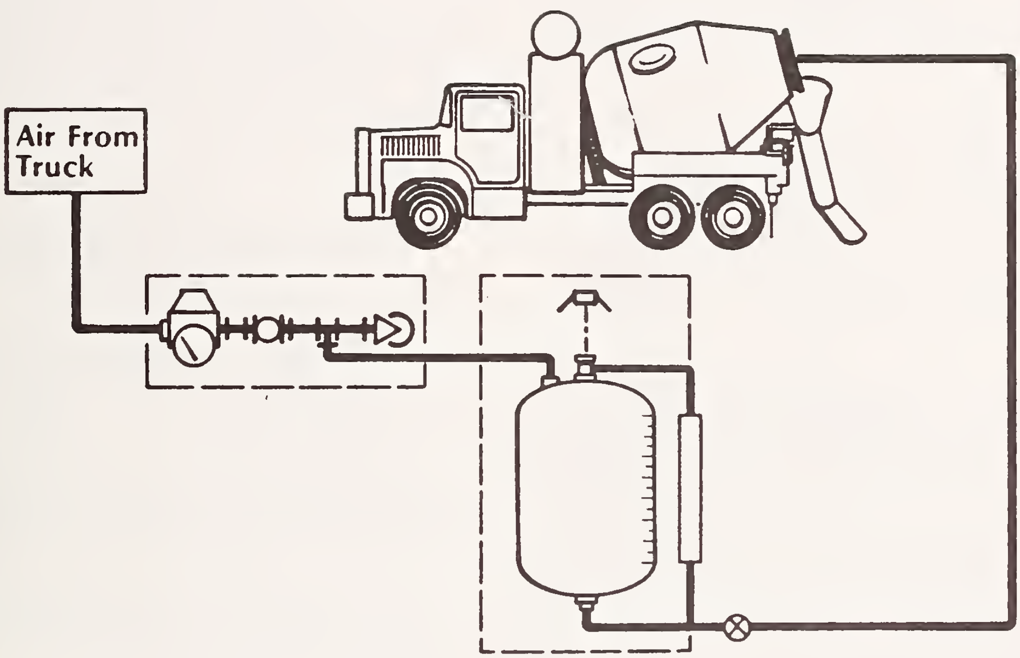

FIGURE 63. ADMIXTURE DISPENSER SYSTEM FOR USE ON
A READY-MIX TRUCK

2. Dosage of A/E agent necessary to achieve desired air content.

3. Time-of-Set of Concrete (C403-77).

4. Compressive Strength of Concrete (C39-72) at 1, 3, 7, and 28 days.

5. Parameters of the Air-Void System in Hardened Concrete (C457-71).

In addition, it is recommended that a slump loss test similar to that used in the present study (see Section 4.2.1) be utilized so as to anticipate any serious problems in this regard.

Secondly, after laboratory tests have been completed, at least one full-scale batch should be prepared using the dosages and mix cycle employed in the laboratory program. If problems are encountered, this batch can be used on a noncritical job and adjustments can be made so that problems will be minimal during actual production.

The use of SWR is advisable only when the producer has good control over the uniformity of his materials. Frequent changes in aggregate and cement suppliers will lead to large variations in concrete performance. To avoid the necessity of frequent preparations of trial batches, the same materials should be used in all phases of a project where the use of SWR is contemplated.

10.8.2 Equipment

No major modifications in standard ready-mix equipment are needed. An automatic admixture dispenser unit specifically tailored towards introduction of SWR into a transit mixer is advisable. Such equipment is available from one manufacturer (ICI, U.S., Wilmington, Delaware) (see Figure 63).

It should be noted that if the recommended mix cycles are used, that is, the SWR being added at the jobsite, the initial mixture will essentially have the consistency of SSD sand. Depending on the aggregates used, this mixture may be highly abrasive. This will require increased maintenance of the mixers and more vigilant lubrication schedules.

10.8.3 Batching Procedures

The initial mixture may be prepared either in a central mixer or in a transit-mix truck. If a central mixer is to be used, a preliminary batch should be prepared to ensure that the dry mix can be adequately transferred to the Ready-Mix truck. A tilt-drum type mixer having an efficient discharge system would be most applicable.

Normal batching procedures commonly in use at the given plant can be followed. The air-entraining agent should be added to the initial mixture. While this increases the amount of air-entraining agent which is required, see Table 81, it eliminates on-site control problems inherent when more than one admixture is to be used.

10.8.4 Mixing and Transportation

After charging, the mixer (either Tilt-Drum or Transit Mixer) should be run for 5 minutes. The mix can then be discharged into the ready-mix truck, or if a transit mixer is used, be transported immediately to the site.

TABLE 81

Amounts of A/E Agent Required in Initial Mix

SWR	A/E Agent Dosage 1/
Mighty-150	3-4
Melment L-10	5-7

1/ Multiply amount needed in normal mix without a SWR by these figures.

All the water should be added to the initial mixture. Retempering should be avoided if at all possible.

Transportation time should be as short as possible. If haul times exceed 1 hour, increased amounts of SWR may be needed at the site. Agitation should be used during transport.

10.8.5 Addition of Super-Water Reducer

Super-water reducer should be added only when the truck is in position for discharge of concrete. The drum should be reversed until the entire load is close to the chute. The drum is then stopped and the SWR is added, either manually or with an automatic dispensing device. The drum is then placed into forward motion for 3-5 minutes of additional mixing. At this point the concrete can be discharged.

If loss in workability during placement is greater than anticipated, the mix can be retempered by addition of SWR.

Approximately 0.1-0.2% of admixture on a solids basis added every 15 minutes is required to maintain slump above the 2-in. (50 mm) level. This is equivalent to 2.8-5.6 fl oz/bag (1.9-3.8 ml/kg) of Mighty-150 and 5.7-11.4 fl oz/bag (3.9-7.8 ml/kg) of Melment L-10.

In hot weather retarders can be used to reduce the rate of slump loss. Retarders based on hydroxcarboxylic acids have been found to be most effective. The retarder should be used at approximately 50% of the manufacturers recommended dosage for normal concrete. When using a retarder the dosage of SWR may need to be reduced to obtain the desired slump. The retarder should be added to the batch after all SWR has been thoroughly intermixed with the other ingredients.

10.8.6 Quality Assurance Procedures

10.8.6.1 Control of Slump

Specified slump for concrete containing SWR shall be 6 $\pm$ 1 in. (152 $\pm$ 25 mm) after discharge of approximately 15% of the truck load. Higher slumps are permissible if no obvious indications of segregation are evidenced. In most cases, concretes containing SWR will lose slump rapidly during the process of placing an entire truck load. For this reason, slump should be measured at 15 minute intervals, and the load should be retempered with additional SWR if slump falls below 2-in. (50 mm).

10.8.6.2 Control of Air Content

Freshly mixed concretes containing SWR will exhibit a loss of air in the plastic state. To compensate for this loss, the initial air content of a mixture prepared with maximum aggregate size of 3/4 in. (19 mm) should exhibit an initial air content of 8 $\pm$ 1%. Air content should be remeasured at 15 minute intervals. If air content drops below 6%, additional A/E agent should be added to the batch.

10.9 Use of Super-Water Reducers in Concrete Mobile Operations for Production of Dense Portland Cement Concrete Overlays

10.9.1 Background

Low water-cement ratio, high cement content concrete mixtures have proven to be an effective means of providing high strength, durable overlays over existing concrete pavements and bridge deck riding surfaces. These mixtures are frequently referred to as "dense" concretes or "Iowa Low Slump" concretes. Their major disadvantage is that due to the low water-cement ratio employed, the mixture must be subjected to intense vibration in order to be sufficiently compacted to the required density. A typical mix design is given in Table 82.

Depending on the particular aggregates and cement used, the slump will vary between zero and approximately 1-in. (25 mm) if no workability aid is used. Therefore, super-water reducers can be used to advantage in increasing the slump to 2-3 in. (51-76 mm) so as to obtain a more workable concrete.

TABLE 82

Mix Design1/ for Dense Concrete

Material	Quantity - SSD lb per cu yd2/
Coarse Aggregate	1,370
Fine Aggregate	1,370
Cement	823
Water	288

1/ Mix Design as specified by Iowa Department of Transportation, Specification No. 796.

2/ To convert from lb/yd^3 to kg/m^3 multiply by 0.594.

One of the most effective ways of producing such a concrete is through use of continuous volumetric batching and mixing in a unit termed a "Concrete Mobile."[R] Up to 10 yd^3 (7.6 m^3) of concrete can be produced from one unit. The materials are carried separately to the job site, then mixed immediately before discharge. Thus, there is no "haul time" during which workability may be lost.

10.9.2 Pre-Construction Procedures

One of the main advantages in the use of a concrete mobile is that if the unit has been properly calibrated, no trial batches need be run in the laboratory or at a central batch plant. Small portions of the materials can be mixed at the job site simply by running the unit for about 30 seconds for each trial. Material dispensing devices can then be adjusted so as to achieve the specified slump and air levels.

As no severe slump loss problems were noted in these mixtures, pre-construction tests for slump loss are not necessary.

[R] IRL Daffin Assoc., Lancaster, PA.

Likewise, no problems in achieving desired air contents or satisfactory air-void systems have been encountered, most likely due to the high cement content and low SWR dosage requirements in these mixtures.

10.9.3 Equipment

A combination materials transporter and mobile mixer, termed a "Concrete Mobile,"[R] is recommended for this application. Units are available in capacities ranging from 4 yd^3 (3.1 m^3) to 10 yd^3 (7.6 m^3). Detailed specifications on each unit are available from the manufacturer.

In order to assure adequate job performance, the unit should be calibrated prior to each job. Cement is dispensed through a rotary van-type metering feeder onto the main conveyor belt. The cement meter is calibrated by filling the bin with cement and dispensing the cement at a fixed rate into 55 gal (208 L) drums. By weighing the discharged cement the exact cement discharge rate of the unit can be calculated. The sand and coarse aggregates are dispensed through hand wheel operated gates onto the main conveyor belt. The dry rodded unit weights of the materials must be determined in advance. Once this is done, the materials are discharged into 1-cu ft (0.028 m^3) containers, and the maximum gate opening is adjusted so that the dry unit weight of material is dispensed within the prescribed number of cement meter revolutions (the cement meter is geared to the main conveyor belt).

Water discharge is calibrated in a similar manner, except that the calibration is done by volume rather than weight. Admixture discharge can be monitored via flowmeters mounted on the tanks during actual operation. As the flowmeters are pre-calibrated at the factory, no user calibration is necessary.

The above description is necessarily concise. The user must, however, thoroughly read the information supplied with each unit as to exact details of calibration and operating procedures for the "Concrete Mobile". Technical service representatives of the manufacturer can be consulted during initial familiarization with the unit. In addition, the user should be cognizant of the stipulations set forth in ASTM C685-79 "Standard Specification for Concrete Made by Volumetric Batching and Continuous Mixing."

10.9.4 Batching and Mixing Procedures

The user should ensure that all material bins are clean prior to charging with new materials. The bins should be swept out or washed, if washed they should be subsequently dried. Admixture tanks should be flushed before filling with new solutions.

All dry material bins are top loaded. The cover should be clamped on the cement bin once it is filled. Dry rodded unit weight and moisture content of aggregates must be determined in advance.

Admixtures must be diluted prior to charging the tanks. Most mobile units are equipped with two flowmeter systems. The first system "HI-FLO" is calibrated in quartz/min (L/min). The second "LO-FLO", is calibrated in oz/min (ml/min). SWR admixtures are used with the "HI-FLO" system, A/E agents with the "LO-FLO" system.

The A/E agent is diluted 5:1 with water. The diluted solution is then used to fill the "LO-FLO" tank. The flowmeter setting is determined in accordance with the directions in the manufacturers' handbook.

The SWR agent is diluted so that the recommended dosage in fl oz/bag of cement (ml/kg of cement), is contained in 1 quart (0.95 L) of diluted solution. The diluted solution is then used to fill the "HI-FLO" tank. The flowmeter setting is determined in accordance with the directions in the manufacturers' handbook.

The dosage of SWR needed to achieve an initial slump of 2-3 in. (51-76 mm) for the mixture specified in Table 82 can be estimated using one of the techniques described in Section 10.4. A correction factor of 0.3 is applied to the computed dosage for the overlay mix.

The dosage of A/E agent needed to obtain the specified air content of 6-7 percent will be approximately 4-5 times that used in a normal concrete mixture. For example, if the A/E agent is normally used at a dosage of 1 fl oz/bag of cement (0.7 ml/kg), 4.5 fl oz/ bag (2.8-3.5 ml/kg) of cement should be used in the mixtures containing SWR.

The unit should be run initially until at least 2 ft^3 (0.06 m^3) of concrete has been discharged. This takes about 20-30 seconds. An additional 2 ft^3 (0.06 m^3) sample should then be discharged and tested for slump, air, and unit weight. If slump is out of specification, the SWR dosage should be adjusted using the

recommendations in Table 75. If air content is out of specification dosage should should be adjusted based on previous experience.

The actual design and placement of concrete overlays was not a part of this project. Information on specific equipment and procedures to be followed can be found in a number of publications (37,38,39). Although SWR have not been field-tested extensively using Concrete-Mobiles in these applications, no major modifications to existing equipment or procedures are anticipated. In fact, one may be able to use less severe vibration and increase the rate of production due to the large increases in workability afforded by the super-water reducing admixtures.

11. Summary and Conclusions

11.1 Six commercially available super-water reducers have been identified as belonging either to the chemical classes of sulfonated condensation products of naphthalene and formaldehyde, sulfonated condensation products of melamine and formaldehyde, or a blend of the two. The majority of such admixtures belong to the naphthalene class. Minor components such as inorganic sulfate, chloride, and alkalies are also present, however, these appear to have little effect on the performance of the various admixtures.

11.2 A "mini-slump" test procedure based on flowability of neat cement paste has been used to determine dosage requirements and to examine the loss of workability with time. Dosage of super-water reducers needed to obtain a given flow pat area is proportional to the C_3A content, alkali content, and fineness of the cement. The dosage for a particular cement is usually greater when melamine-based products are used. Loss of pat area with time is much greater in pastes containing super-water reducers than in admixture-free cement pastes, especially in cements having high C_3A contents. A delay in addition of admixture by a few minutes decreases the dosage needed to obtain a given pat area, and also, in some cases, decreases the rate of loss of pat area with time.

11.3 Super-water reducers can be blended with conventional water-reducers based on glucoheptonates, hydroxycarboxylic acids, lignosulfonate, or corn syrups. In this manner, the proportion of the more expensive super-water reducers can be reduced up to 30 percent. In some cases, however, severe set retardations can result when these blended admixtures are employed.

11.4 In all cases, concrete mixtures prepared with super-water reducers at low ($\leq$0.35) water-cement ratios, exhibit a higher rate of loss of workability with time ("slump loss") then corresponding control (admixture-free) mixtures. The problem is especially severe in mixtures of moderate cement content produced in central-mix type operations. In some cases, the mixture may become unworkable within 20 minutes after addition of admixture. The use of super-water reducers is not recommended for central-mix operations when concrete is subsequently transported to the job site in non-agitating vehicles.

11.5 A number of means are available for mitigating the slump loss problems in concretes containing these admixtures. Among these are:

11.5.1 Increase dosage of super-water reducer so as to obtain an initial slump between 5-6 in. (127-152 mm).

11.5.2 Delay addition of super-water reducer by 3-5 minutes if agent is to be added at the plant, or, preferably, add super-water reducer at the job site immediately prior to placement.

11.5.3 Add one-half the normal dose of conventional water reducer to the concrete and adjust the dosage of super-water reducer so as to achieve an initial slump between 5-6 in. (127-152 mm).

11.5.4 Redesign concrete mixture so as to increase paste content while maintaining water-cement ratio. Adjust dosage of super-water reducer so as to achieve an initial slump between 5-6 in. (127-152 mm).

11.5.5 Produce concrete by on-site volumetric batching and continuous mixing ("Concrete Mobile").

11.6 Some retardation in setting times can be expected when super-water reducers are used, especially at higher dosage rates. The extent of retardation varies considerably with the particular cement and admixture being used. An accelerating admixture may be used to offset some of the retardation; however, this may contribute to an increased rate of slump loss.

11.7 When super-water reducers are added at the job site ("delayed addition"), the dosage needed to obtain a given slump varies inversely with temperature below 73°F (23°C). Approximately 30-40 percent more admixture will be needed at a temperature of 45°F (7°C) than at a temperature of 73°F (23°C).

11.8 When producing concrete containing super-water reducers in hot weather, a significant increase in rate of slump loss is to be expected. This can be offset by the use of conventional water-reducing/retarding admixtures (see Section 11.5.3).

11.9 The rate of loss of air from air-entrained concretes containing super-water reducers is greater than that from corresponding control (admixture-free) concretes. Accompanying this loss of air is a shift in air void size distributions toward coarser void sizes, which decreases specific surface area and increases spacing factors outside commonly accepted limits. In some cases, acceptable void size parameters may be obtained by an increase in plastic air content into the range of 7-8 percent. The success of the approach is a function of the particular super-water reducer, air-entraining agent, cement, and concrete mix design and procedure employed.

11.10 Concrete specimens produced from laboratory control and super-water reduced concretes were tested for a wide variety of physical properties. Gain of strength with time, plastic shrinkage, elastic properties, chloride permeability, sulfate resistance, and resistance to D-cracking were all improved in concretes produced using super-water reducers. Little differences in creep, drying shrinkage, freeze-thaw resistance, or thermal expansion between control and super-water reduced concretes were seen. Resistance to abrasion was somewhat lower in the concretes containing super-water reducers. Resistance to deicer-scaling was considerably lower in super-water reduced concretes. Void spacing factors in concretes containing super-water reducers were found to be greater than generally recommended.

11.11 Super-water reducers were added to full-scale concrete batches produced in a ready-mix operation. Slump loss was exceptionally severe, and significant accelerations of setting time were seen. Air-void system parameters were excellent; however, poor durability of aggregates used made freeze-thaw test results difficult to interpret.

11.12 High cement content, low water-cement ratio concrete based on the "Iowa" overlay design was produced using a continuous mixer ("Concrete Mobile"®). Super-water reducers were used as workability aids. Slump loss was moderate, high strengths were achieved, and the majority of mixtures exhibited excellent air-void systems and good durability.

11.13 A users manual describing the use of super-water reducers in highway applications is included in this report. General background information, guidelines describing determination of dosage requirements, and techniques for minimization of slump loss are given. Also included are recommendations specific to the use of super-water reducers in standard ready-mix operations as well as with novel Concrete Mobile® units.

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APPENDIX A

Spectrophotometric Characterization of Admixtures

1. Infrared Analysis

Samples were taken from each of the seven admixtures. Pressed KBr pellets were prepared as described in ASTM C494, Section 18.1. Scans were made on a Beckman Model 4240 Infrared Spectrophotometer at 300 cm^{-1}/min. over the range of 300 to 3600 cm^{-1}. The spectra are presented in Figures 64A-G.

The first five admixtures exhibit very similar spectra. The absorptions at 620 cm^{-1} and 470 cm^{-1} are specific for a naphthalene structure. The naphthalene fused ring structure may be considered as two separate benzene rings, with the two fused carbon atoms interpreted as two adjacent substitution positions for each benzene ring. In the case of condensation products, additional naphthalene rings are substituted at the other ring positions, $-CH_2-$ bridging the rings (see Figure 1). Although it is not possible to determine the degrees of polymerization (n) from the IR spectra, minor differences in the "fingerprint" region (300-700 cm^{-1}), indicate the size distributions are different. The various bands in the region of 400-1600 cm^{-1} are typical of substituted aromatics.

The bands at 1115 cm^{-1} and 675 cm^{-1} are strong and characteristic of sulfonated aromatics. A likely impurity for these materials is the sulfate ($SO_4^{=}$) ion. It has absorbances at 1115 cm^{-1} and 620 cm^{-1}. Its effect would be to increase the intensity of these bands at high concentrations. As the highest sulfate concentration found (Lomar D) was only 10 percent of the total solids, it would be difficult to resolve the differences in these cases. This is supported by the wet chemical analysis (see Table 2), which showed sulfate ion to be present in all these admixture formulations.

The spectrum for Melment L-10 (Figure 64F) shows broader, more diffuse bands, typical of a larger polymer. In this case, the single sharp absorbance at 810 cm^{-1} is typical of the melamine structure. The sulfonate absorbances, however, are poorly resolved, and the 675 cm^{-1} sulfonate absorbance present in the naphthalene compounds is absent. The sulfate absorbance at 620 cm^{-1}, however, is also present in the Melment spectrum.

It was hypothesized that FX-32C was a blend of naphthalene and melamine condensation products. To test this hypothesis, a mixture of Mighty-150 and Melment L-10 was prepared and subject to IR analyses. It can be seen from Figure 64G, that the spectra are practically identical, indicating that FX-32C is indeed a blend of the two generic classes of SWR.

2. UV Spectra

Ultraviolet (UV) spectrophotometry is primarily used in quantitative analyses of organic solutions. If a compound conforms to Beer-Lambert's law, the log of the concentration being proportional to the absorbance, a series of standard solutions can be prepared and this calibration can be used to determine the concentration of any unknown solutions. When used for identification purposes, the UV spectra are not as useful as Infrared, as many substances containing chromphores (double bonds) will show very similar spectra. However, differences in the spectra should indicate that different compounds are present when two solutions are compared.

Each admixture was used to prepare aqueous solutions (in distilled water) of concentrations 6,000 ppm, 600 ppm, 30 ppm, and 3 ppm. A preliminary scan on a Beckman Model ACTA cIII indicated absorbances in the 200 nm - 300 nm region. Each admixture was then scanned in this region at each dilution. The most dilute (3 ppm) samples showed two distinct absorbance peaks for each admixture. Absorbance data are shown in Table 83. The five admixtures known to be naphthalene-based show similar peaks and absorbances. The spectra for Melment L-10 was not quantitative, the single absorbance maxima shifting between 200-250 nm depending on the concentration. This could have been attributable to the flourescent dye added by the manufacturer of this product. One can also see that although the positions of the absorbance maxima for FX-32C are comparable to those of the naphthalene-based products, the absorbances are less, indicating dilution by another material. This further substantiates the hypothesis that FX-32C is a blend of both types of SWR.

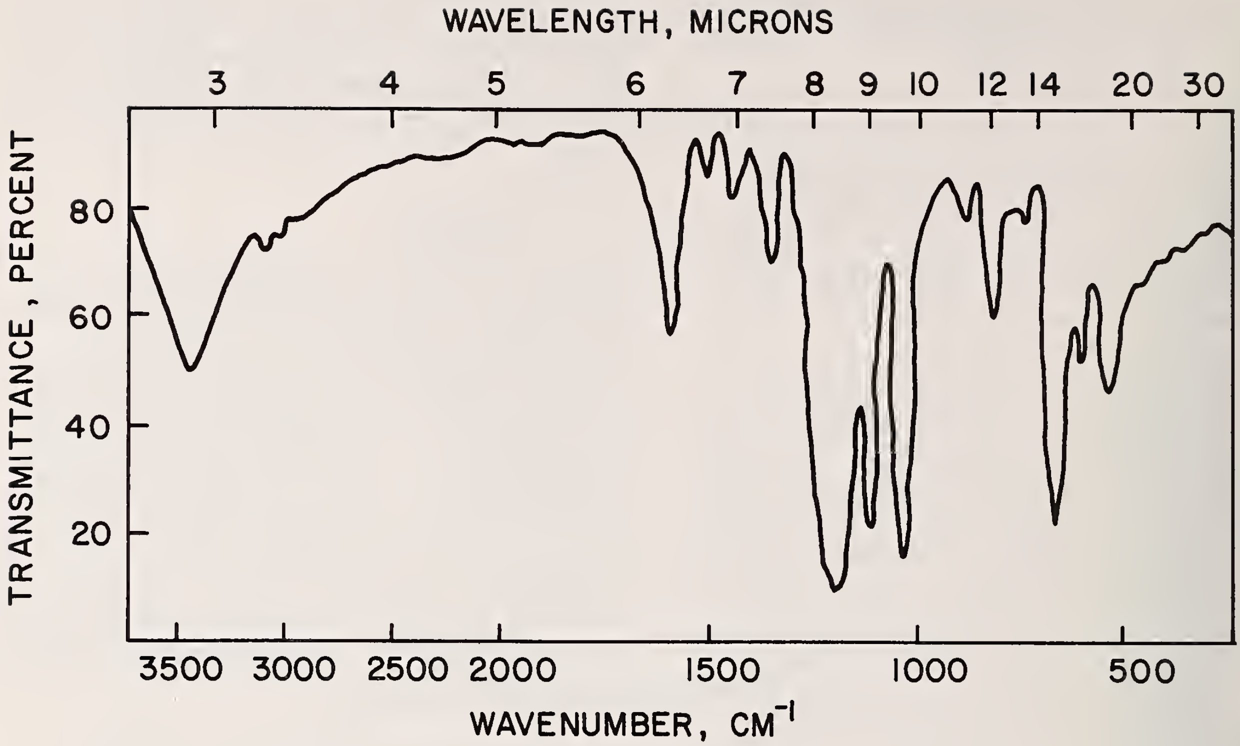

FIGURE 64A. MIGHTY-150

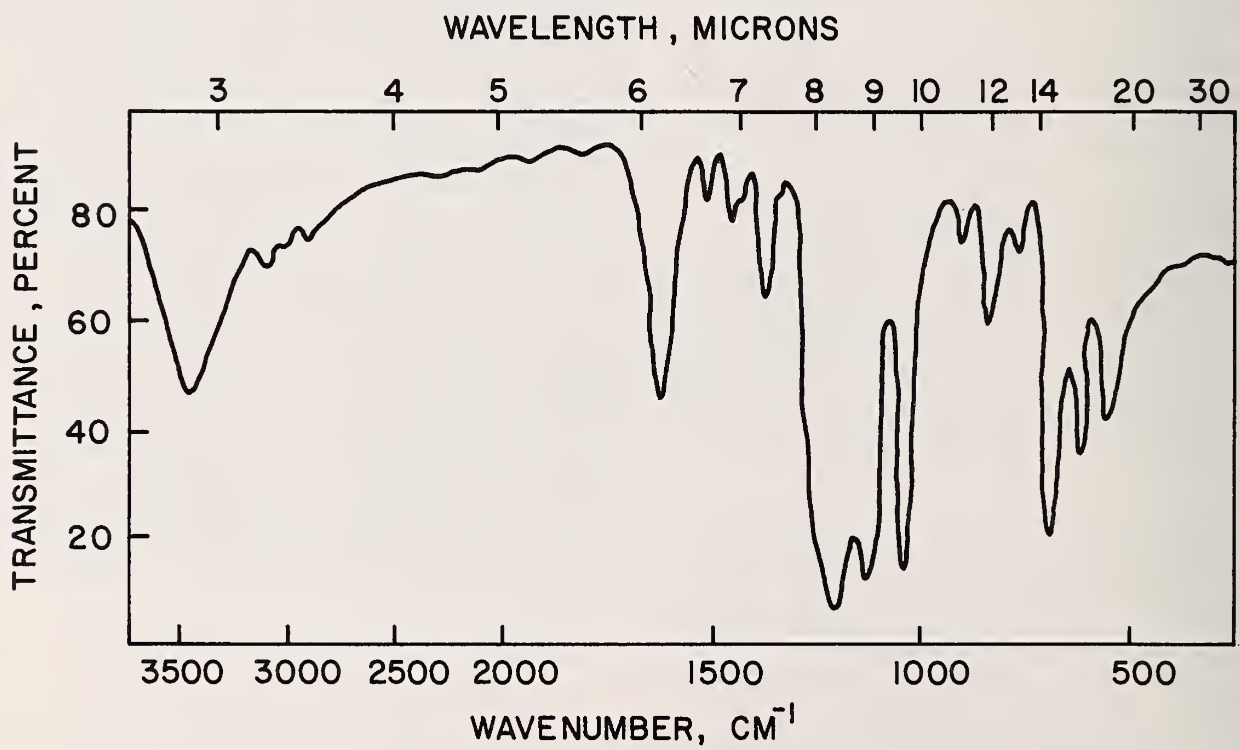

FIGURE 64B. LOMAR-D

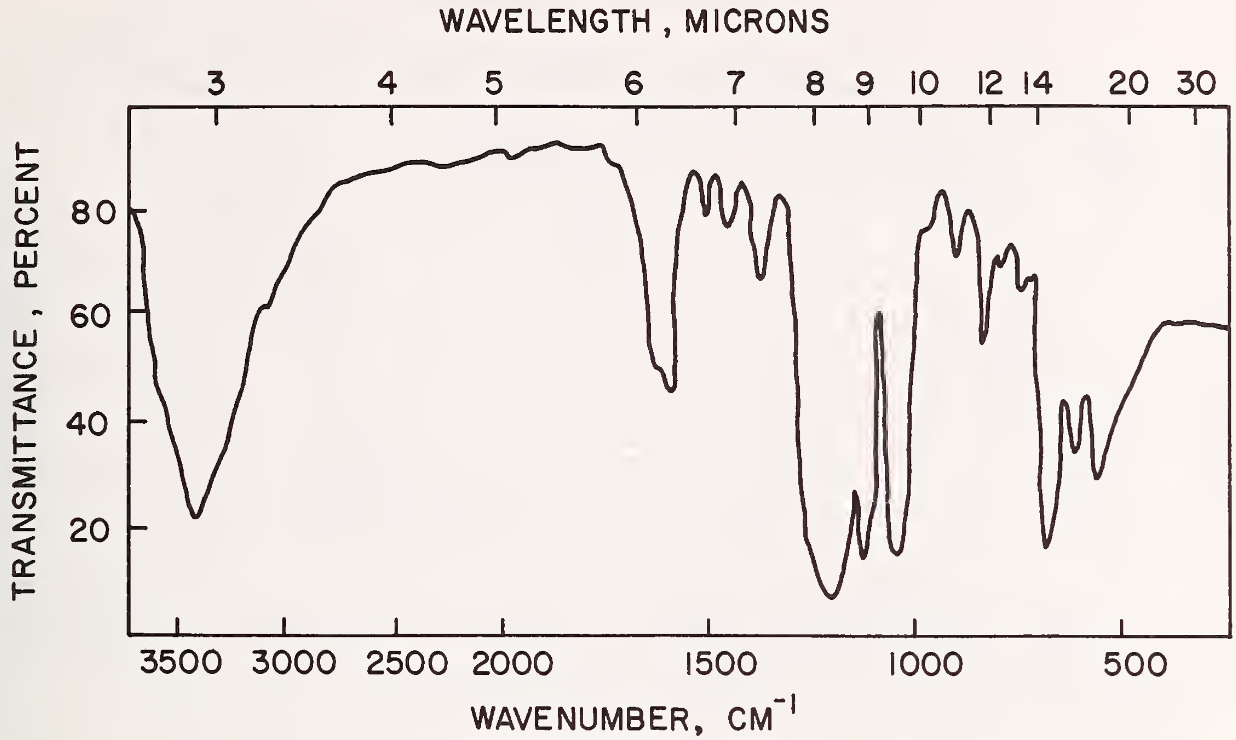

FIGURE 64C. SIKAMENT

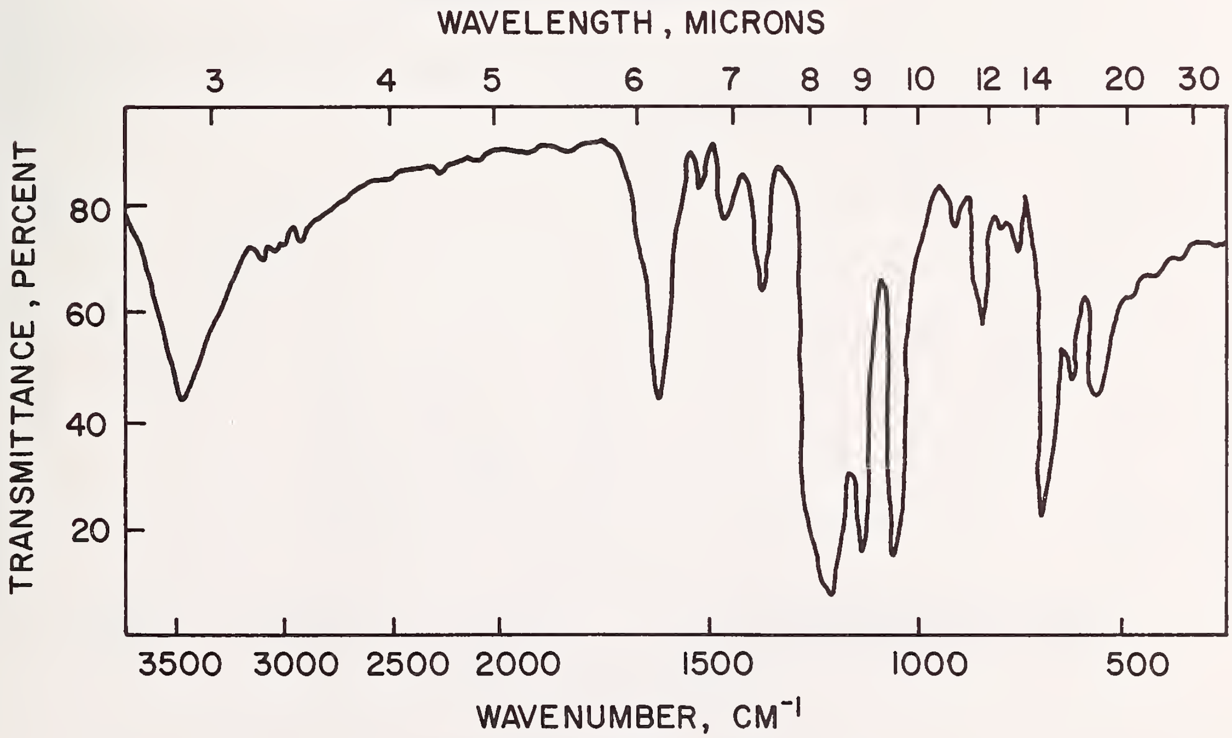

FIGURE 64D. WRDA - 19

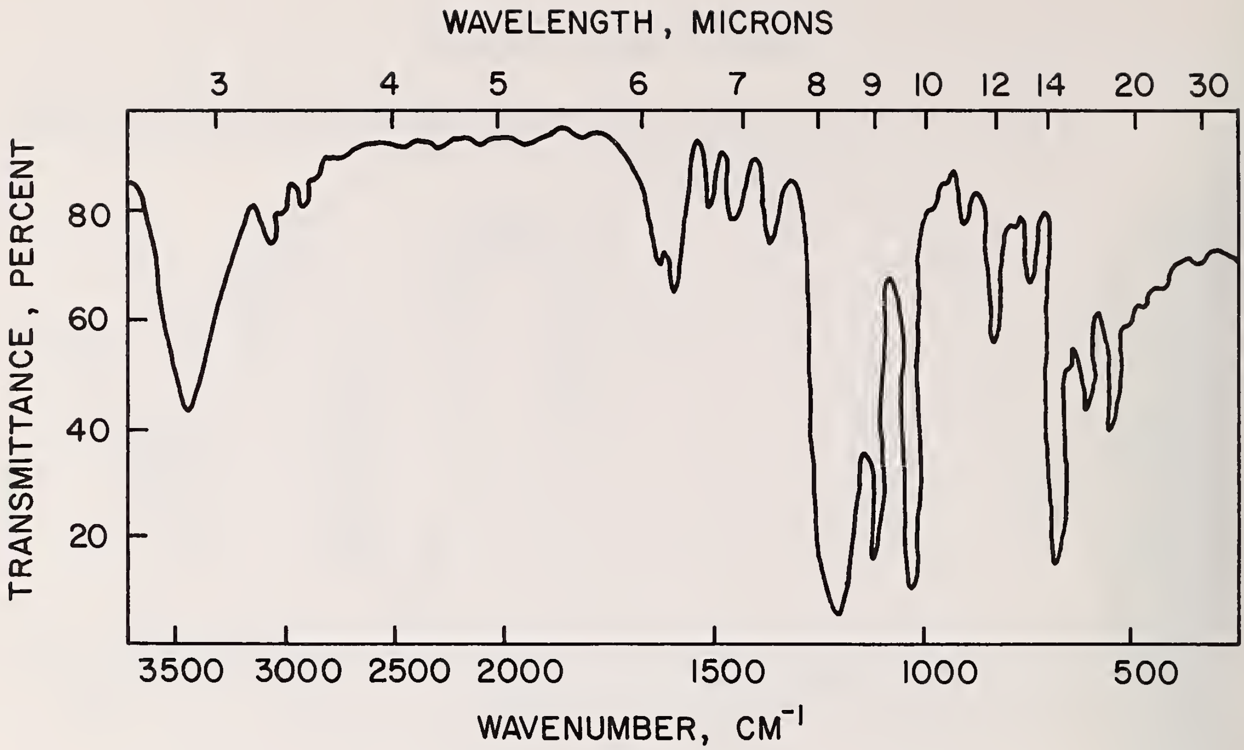

FIGURE 64E. ALKANOL

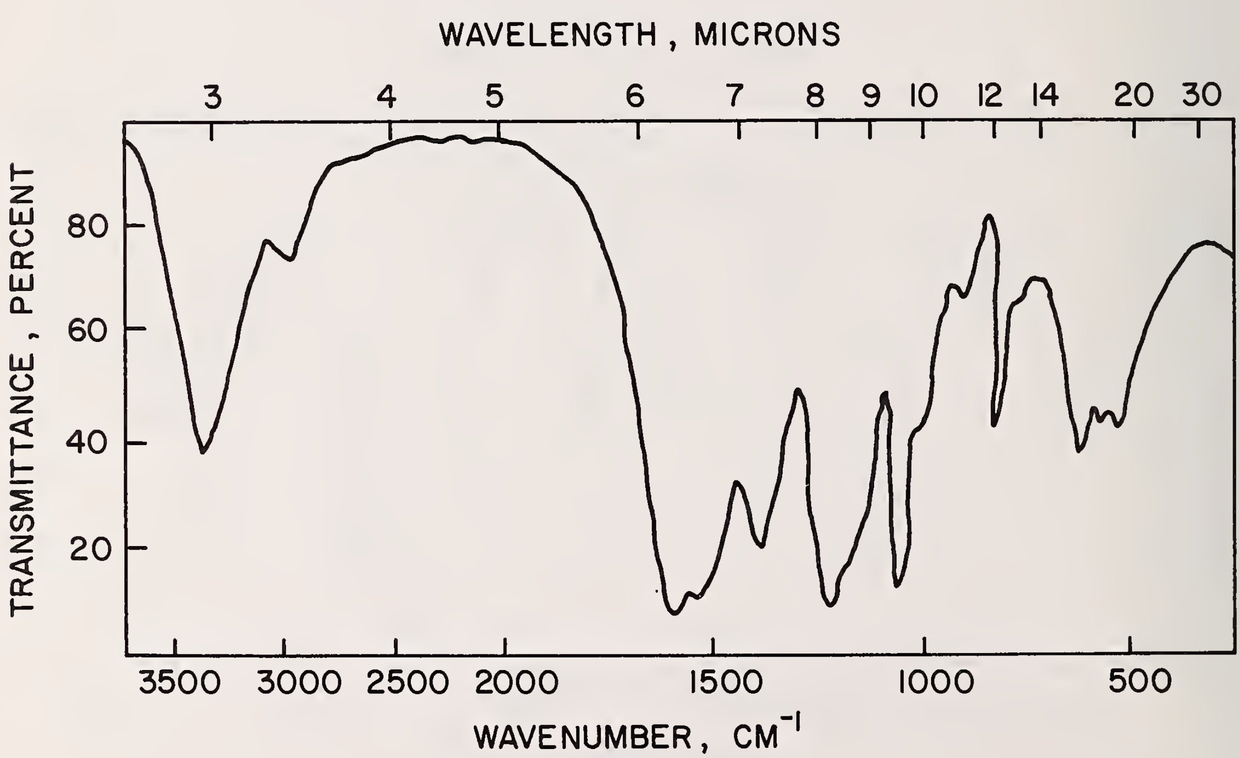

FIGURE 64F. MELMENT L-10

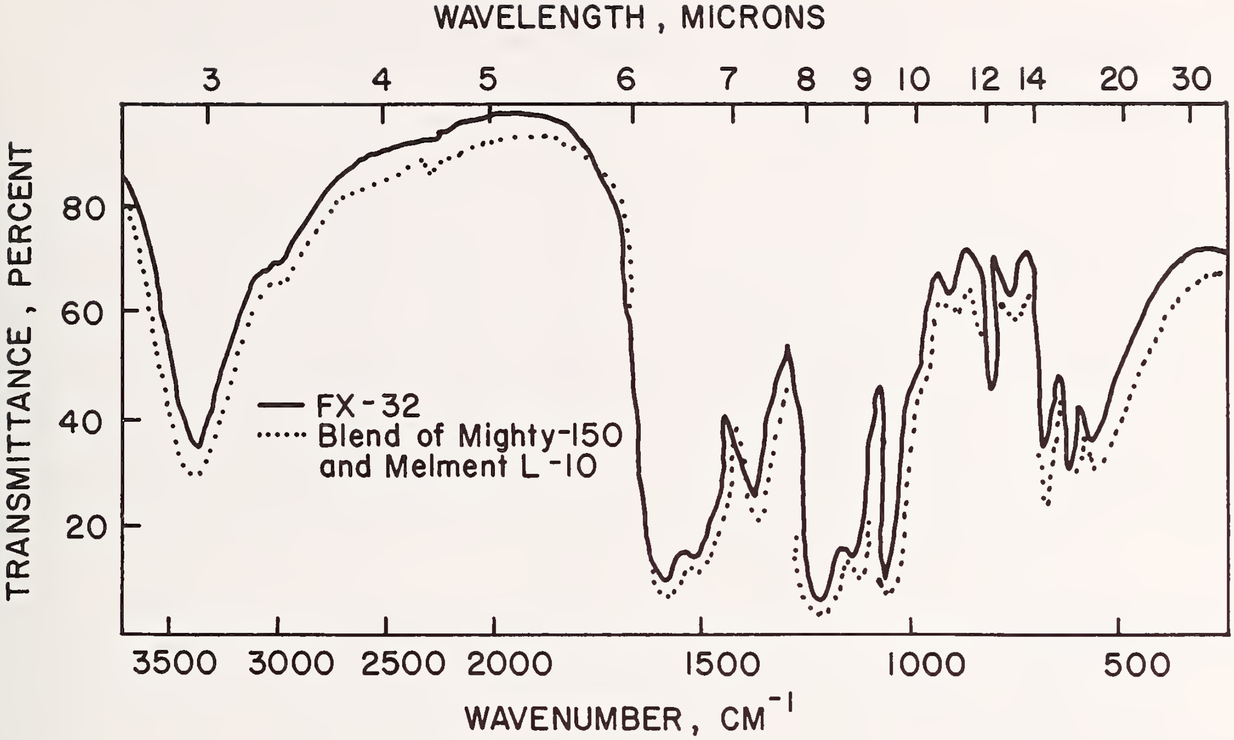

FIGURE 64G. FX-32 VERSUS A BLEND OF MIGHTY-150 AND MELMENT L-10

TABLE 83

Summary of UV Spectrophotometric Data For Seven Admixtures

Admixture	Apparent $A_{MAX}(1)$ (nm)	Apparent $A_{MAX}(2)$ (nm)	$A(\text{mg solids})^{-1}\text{ml}^{-1}\text{cm}^{-1}$ for A(1)	for A(2)
Alkanol	226	285	186	18.8
Lomar D	227	293	166	21.3
Mighty 150	227	292	161	21.7
Sikament	228	290	183	22.0
WRDA 19	227	293	160	22.0
Melment L-10	varies w/conc.	none	varies w/conc.	0.0
FX-32C	224	293	112	8.6

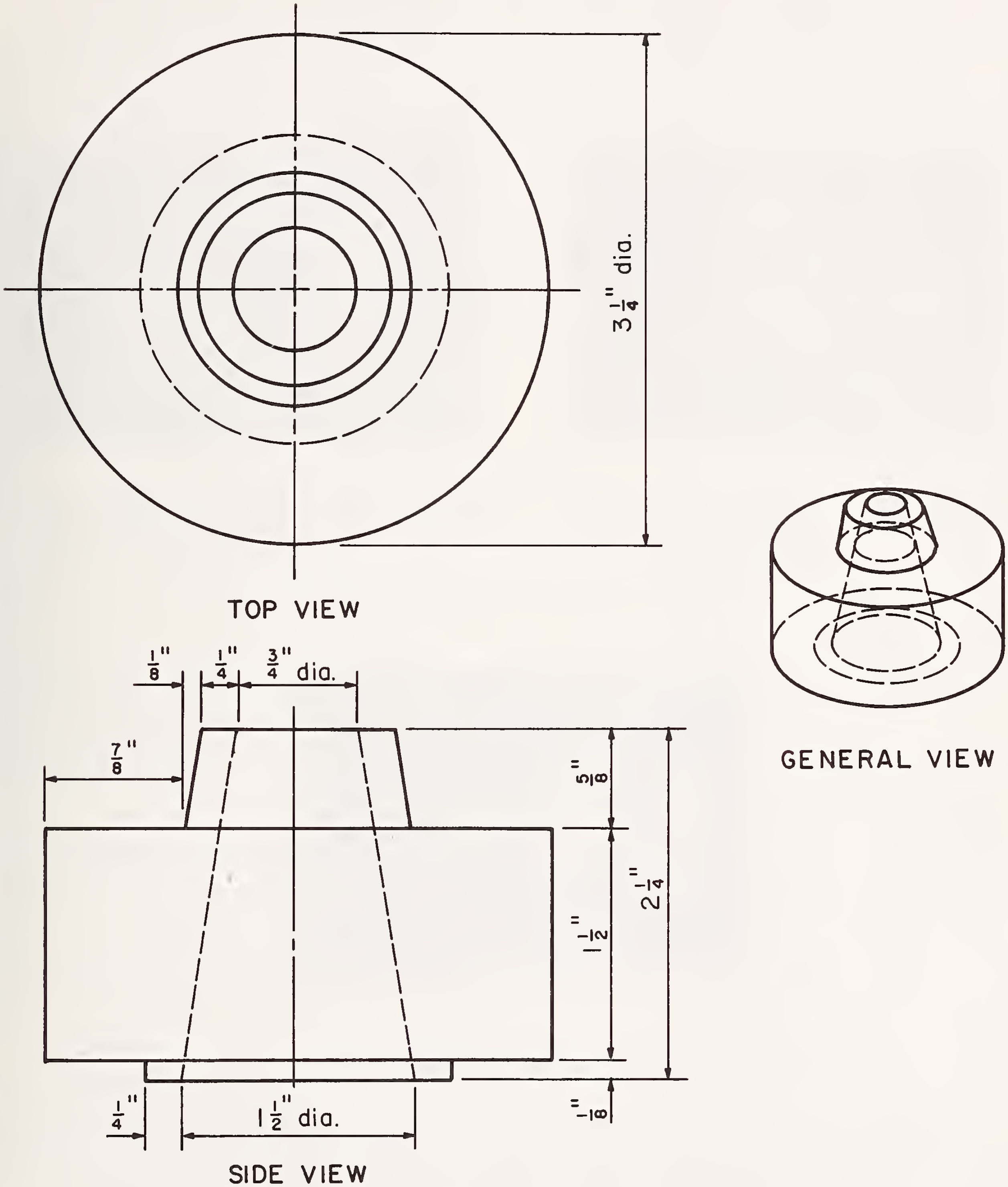

FIGURE 65. DETAILS OF MINI-SLUMP CONE

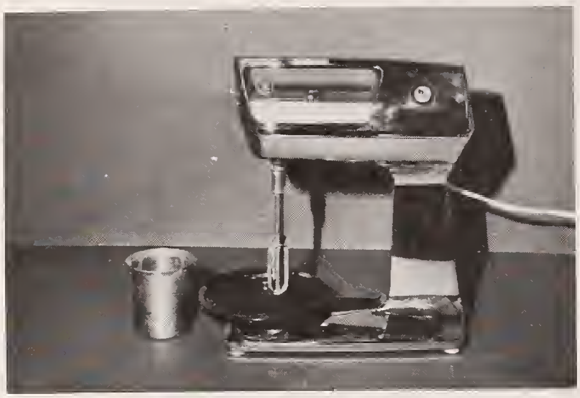

FIGURE 66A. MIXER USED FOR CEMENT PASTES

FIGURE 66B. MINI-SLUMP CONE AND MIXING VESSEL

FIGURE 66C. PATS FORMED IN MINI-SLUMP TEST

FIGURE 66. EQUIPMENT USED IN MINI-SLUMP TEST

APPENDIX B

Mini-Slump Method

1. Equipment

The mini-slump method is a technique developed at the Portland Cement Association by Dr. David Kantro. It is used to assess the consistency of neat cement pastes, and has found considerable application in the evaluation of the effects of chemical admixtures on cement pastes. Since these paste mixtures can become quite fluid, it is more practical to measure the base area of the pat formed during the test, than to measure the slump as in a concrete test. The test has the advantage of rapidity and small sample size, such that many tests can be performed in a few hours by one person.

The mini-slump cone is fabricated out of solid acrylic material. The dimensions are in the same proportions as the standard ASTM C143 slump cone (1). The details of the miniature cone are shown in Figure 65. The wide flange serves to collect excess paste when the top surface of the paste is levelled to the height of the cone. The lower surface of the cone is relieved so that only a 1/4-inch (6.4 mm) wall thickness remains. This prevents the lower surface from impeding the paste flow as the cone is lifted.

Mixing is done with a commercial "kitchen" mixer (Hamilton-Beach Model 40-5) (Figure 66A). A 250 ml stainless steel beaker is used as a mixing vessel (Figure 66B). The mixer is operated at high speed (approximately 250 rpm) during mixing.

The quality of the surface onto which the mini-slump cone is placed is important. The cone itself should be placed on a flat sheet of acrylic material 1/4-inch (6-mm) thick which is laid on top of the laboratory work bench. A 2-inch (50-mm) diameter x 4-mil (0.1-mm) polyethylene film disc is placed directly under the cone to facilitate release of the sample.

2. Technique

2.1 Pat Area Determination

The following procedure is used for carrying out the "mini-slump" test:

1. 70 g of cement and the desired quantity of water are placed into the 250 ml stainless steel beaker.

2. The mixer is run at high speed for 2 minutes. A rest period of 3 minutes follows, during which the mixing bowl is covered to prevent evaporation. This is followed by a final 2 minute mix. This cycle is similar to that recommended in ASTM C192 (2), used to avoid "brief mix set," and false set.

3. After mixing the sample is placed in the cone resting on the acrylic sheet. As the cone is filled, a small spatula is moved in both lateral and vertical directions to aid in the escape of entrapped air bubbles. For all but the stiffest mixes, the filling procedure takes less than 1 minute.

4. At 1 minute after mixing, the cone is lifted. The lifting must be rapid enough for the cone to remain clear of the flowing paste, but not so rapid that a significant upward momentum is imparted to the paste. The lifting technique becomes particularly critical with very fluid pastes. The "feel" for this operation can be gained from a few trial tests.

5. The pat is allowed to stand and air cure until the following day. By then, the pats are usually strong enough to be moved from the lucite sheet to a piece of paper (Figure 66C). The perimeter of the pat is traced onto the paper and its area is determined with a planimeter. In those cases where the pats cannot be lifted without breaking, the tracing may be made from the underside of the plastic sheet with the pat undisturbed. Larger paste mixes can be used if other test procedures are to accompany the mini-slump test. Larger batches are employed in evaluation of loss of workability with time (Pat Area Loss). In this procedure the entire batch is mixed in a

(1) 1979 Annual Book of ASTM Standards, Part 14 - Concrete and Mineral Aggregates, ASTM C143-78, Section 2.1, page 97.

(2) 1979 Annual Book of ASTM Standards, Part 14 - Concrete and Mineral Aggregates, ASTM C192, Section 5.1.2, page 133.

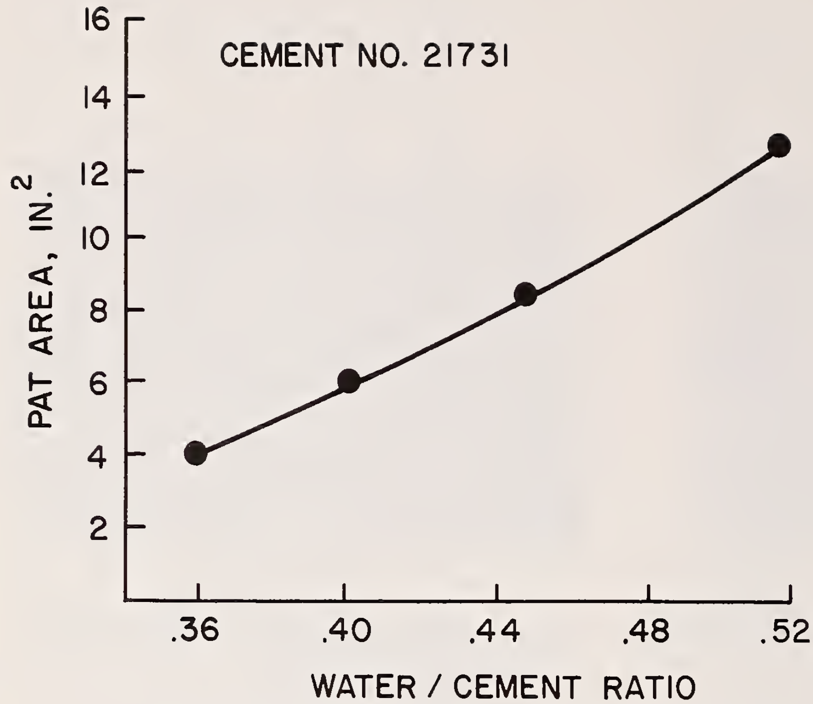

FIGURE 67A. WATER / CEMENT RATIO

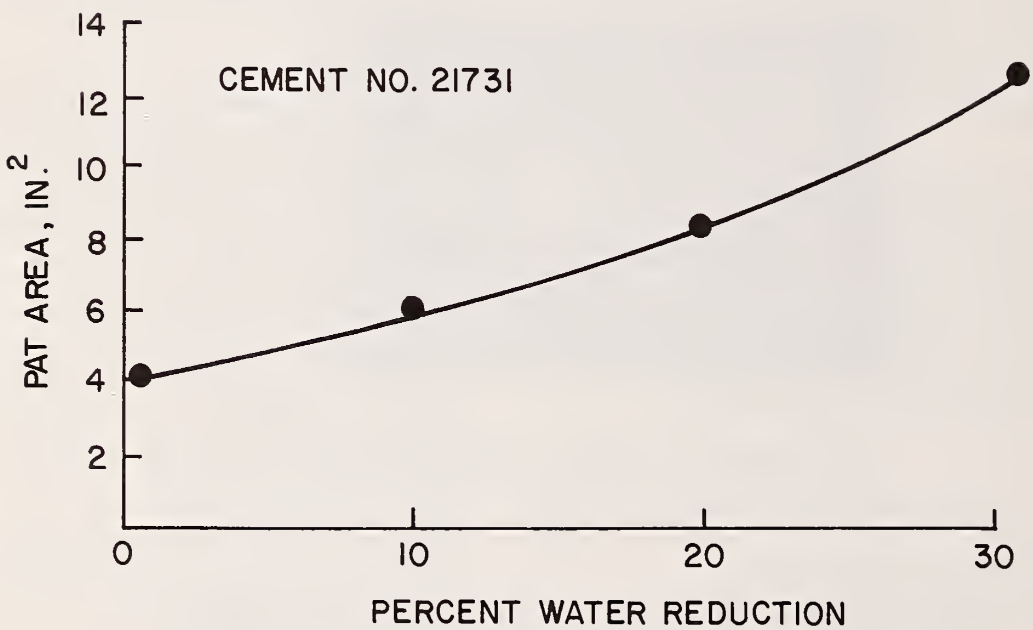

FIGURE 67 B. WATER REDUCTION

FIGURE 67. INFLUENCE OF WATER / CEMENT RATIO AND WATER REDUCTION ON PAT AREA

large vessel, then divided up into small batches poured into 250-ml beakers. These are then allowed to stand for various periods of time, after which each in turn is mixed for an additional two minutes and then poured into the cone.

2.2 Pat Area Loss

Pat area loss evaluations are obtained with a modification of the procedure described above. For this purpose, a mixing regimen described as 2-3-2 X -2 is used, where each 2 represents a 2-minute mixing period, and the 3 and the X represent rest periods. The batch size used depends on the number of values of X to be used. At each value of X a separate pat is made. If 4 values of X are to be used, a 300 gm batch of cement is an adequate size.

The procedure for pat area loss evaluation is as follows:

1. The entire batch (300 gm cement) is mixed using the 2-3-2 cycle in the large stainless steel mixing bowl supplied with the mixer.

2. At an elapsed time of 7 minutes, the batch is quickly distributed to a group of 250 ml stainless steel beakers, one for each value of X to be determined. Mixing is resumed with one of these as quickly as possible.

3. At an elapsed time of 9 minutes, stirring of this batch is halted and the paste poured into the cone. At 10 minutes the cone is lifted. This sample represents a value of 0 for X.

4. At the end of each preselected value for X, another of the sample portions is stirred for 2 minutes, placed in the cone and released at the end of the 3rd minute.

5. This process is continued until all of the pats have been formed onto the acrylic sheet.

3. Calibration and Data Presentation

3.1 Water Reduction

In order to evaluate the water-reducing ability of any admixture, the variation in pat area with water-cement ratio (w/c) of the admixture-free cement paste must first be determined. A series of mixes is prepared with w/c ranging from 0.36 to 0.52. These data (Figure 67A) are used to select some reference w/c level at which comparisons can be made. A suitable level is one at which some small amount of increase in area is observed over the base area of the cone. This allows not only large increases to be measured, but also small decreases which may be observed with some types of admixture. For most cements in the fineness range between 3200 and 4000 cm^2/g (Blaine surface), the 0.36 w/c level is suitable for reference purposes. The plots of area vs w/c ratio are linear for most cements in the range of 0.36 to 0.45. Some deviation from linearity may occur at higher w/c ratios.

Water reduction is expressed relative to the reference w/c ratio. Thus, an admixture which is capable of producing a paste having a pat area which corresponds to a w/c ratio of 0.45 in an admixture-free paste, the "water-reduction" is 20 percent.

$$(100\%) \times \frac{(0.45 - 0.36)}{0.45} = 20\%$$

For a cement having a pat area of 3.98 $in.^2$ (645 mm^2) at w/c = 0.36, the relationship between percent water reduction and pat area will be as depicted in Figure 67B. Using this graph, the pat area obtained when one adds an admixture to this particular cement at w/c = 0.36 can be immediately translated into percent water reduction.

3.2 Pat Area Loss

The pat area loss data can best be interpreted by qualitative examination of plots of pat areas vs time. In order to aid the reader in examination of the large amount of data generated, (see Appendix C), a parameter expressing the percentage area loss after the 1 hour testing time has been utilized. This is termed $\%\Delta A_{60}$, and is given by the following expression:

$$\%\Delta A_{60} = 100 \times \frac{(A_o - A_{60})}{(A_o - A_c)} \quad (5)$$

where:

A_o = initial pat area, $in.^2 (mm^2)$

A_{60} = pat area after 1 hr of test, $in.^2$ (mm^2)

A_c = area of the base of the mini-slump cone, 1.77 $in.^2$ (1,141 mm^2)

The smaller the numerical value of $\%\Delta A_{60}$, the greater the pat area loss.

APPENDIX C

Mini-Slump Series

Dosage Requirements and

Pat Area Loss Data

TABLE 84

Percent Admixture Required (Solids) for 20% Water Reduction

Admixture	Cement					
	21731	21732	21733	MCC-274	LTS-25	MCC-287
Lomar D	0.50	0.39	0.35	0.26	0.30	0.26
Melment L-10	0.50	0.51	0.44	0.32	0.38	0.32
Mighty 150	0.47	0.34	0.39	0.22	0.28	0.23
FX-32C	0.55	0.48	0.48	0.31	0.33	0.30
Sikament	0.44	0.38	0.41	0.28	0.26	0.31
WRDA-19	0.45	0.38	0.37	0.24	0.33	0.28
Alkanol	1.10	0.56	0.99	0.40	0.46	0.51
Mighty RD-2	0.37				0.21	
Plastiment	0.33	0.21	0.21	0.12	0.18	0.25
Daratard HC	0.40	0.44	0.44	0.19	0.17	0.19
Pozzolith 100XR	-	0.43	0.49	0.22	0.31	0.31
Daratard	-	-	-	0.38	0.58	0.48
Lomar D/Plastiment = 9/1	0.47	0.33	0.42	0.24	0.35	0.27
Lomar D/Plastiment = 8/2	0.40	0.37	0.38	0.20	0.30	0.28
Lomar D/Plastiment = 7/3	0.35	0.35	0.43	0.18	0.27	0.26
Melment L-10/Plastiment = 9/1	0.63	0.58	0.46	0.29	0.42	0.31
Melment L-10/Plastiment = 8/2	0.53	0.47	0.51	0.21	0.35	0.28
Melment L-10/Plastiment = 7/3	0.35	0.37	0.50	0.19	0.27	0.25
Mighty 150/Plastiment = 9/1	0.43	0.37	0.36	0.20	0.27	0.24
Mighty 150/Plastiment = 8/2	0.40	0.31	0.42	0.16	0.29	0.24
Mighty 150/Plastiment = 7/3	0.36	0.34	0.39	0.14	0.22	0.25
Lomar D/Daratard HC = 9/1	0.46	0.42	0.52	0.27	0.34	0.26
Lomar D/Daratard HC = 8/2	0.44	0.44	0.55	0.26	0.34	0.27
Lomar D/Daratard HC = 7/3	0.44	0.46	0.50	0.21	0.28	0.31
Lomar D/Pozzolith 100XR = 9/1	0.48	0.40	0.37	0.24	0.33	0.28
Lomar D/Pozzolith 100XR = 8/2	0.50	0.42	0.37	0.23	0.33	0.28
Lomar D/Pozzolith 100XR = 7/3	0.47	0.43	0.43	0.24	0.36	0.26
Lomar D/Daratard = 9/1	0.47	0.44	0.41	0.25	0.37	0.25
Lomar D/Daratard = 8/2	0.49	0.53	0.44	0.38	0.45	0.25
Lomar D/Daratard = 7/3	0.50	0.50	0.48	0.31	0.40	0.27
Lomar D/Daratard = 6/4	0.58					
Lomar D/Daratard = 5/5	0.64					
FX32C/Plastiment = 9/1	0.51	0.44	0.50	0.32	0.25	0.30
FX32C/Plastiment = 8/2	0.49	0.40	0.53	0.23	0.21	0.29
FX32C/Plastiment = 7/3	0.38	0.29	0.40	0.16	0.21	0.31
Sikament/Plastiment = 9/1	0.46	0.37	0.41	0.20	0.23	0.27
Sikament/Plastiment = 8/2	0.42	0.34	0.41	0.17	0.21	0.24
Sikament/Plastiment = 7/3	0.35	0.28	0.32	0.16	0.17	0.19
WRDA/Plastiment = 9/1	0.39				0.25	0.26
WRDA/Plastiment = 8/2					0.21	0.22
WRDA/Plastiment = 7/3					0.20	0.22

TABLE 85

Percent Admixture Required (Solids) for 30% Water Reduction

Admixture	Cement 21731	21732	21733	MCC-274	LTS-25	MCC-287
Lomar D	0.61	0.44	0.46	0.33	0.37	0.30
Melment L-10	0.65	0.54	0.50	0.54	0.42	0.36
Mighty 150	0.60	0.43	0.46	0.32	0.35	0.29
FX-32C	0.69	0.51	0.53	0.46	0.38	0.35
Sikament	0.49	0.46	0.49	0.45	0.34	0.36
WRDA-19	0.57	0.44	0.46	0.37	0.38	0.32
Alkanol	1.25	0.95	1.13	0.58	0.70	-
Mighty RD-2	0.42				0.22	
Plastiment	-	-	-		0.19	
Daratard HC	-	-	-		0.23	0.38
Pozzolith 100XR	-	-	-	0.31	-	0.36
Daratard	-	-	-	0.37	-	0.55
Lomar D/Plastiment = 9/1	0.57	0.41	0.50	0.34	0.39	0.33
Lomar D/Plastiment = 8/2	0.48	0.41	0.47	0.24	0.34	
Lomar D/Plastiment = 7/3	0.41	0.38	0.48	0.22	0.32	0.27
Melment L-10/Plastiment = 9/1	0.75	0.62	0.58	0.37	0.46	0.35
Melment L-10/Plastiment = 8/2	0.57	0.52	0.64	0.27	0.38	0.33
Melment L-10/Plastiment = 7/3	0.49	0.42	0.56	0.25	0.32	0.28
Mighty 150/Plastiment = 9/1	0.54	0.44	0.49	0.26	0.33	0.30
Mighty 150/Plastiment = 8/2	0.48	0.36	0.55	0.20	0.33	0.31
Mighty 150/Plastiment = 7/3	0.51	0.43	0.45	0.20	0.26	0.27
Lomar D/Daratard HC = 9/1	0.53	0.52	0.57	0.39	0.38	0.33
Lomar D/Daratard HC = 8/2	0.59	0.53	0.61	0.29	0.37	0.34
Lomar D/Daratard HC = 7/3	0.53	0.51	0.54	0.25	0.34	0.37
Lomar D/Pozzolith 100XR = 9/1		0.45	0.44	0.37	0.37	0.33
Lomar D/Pozzolith 100XR = 8/2	0.58	0.48	0.53	0.33	0.37	0.34
Lomar D/Pozzolith 100XR = 7/3	0.60	0.50	0.57	0.27	0.40	0.31
Lomar D/Daratard = 9/1	0.57	0.49	0.49	0.45	0.43	0.29
Lomar D/Daratard = 8/2	0.58	0.63	0.53	0.50	0.49	
Lomar D/Daratard = 7/3		0.62	0.55	0.45	0.47	0.34
Lomar D/Daratard = 6/4	0.69					
Lomar D/Daratard = 5/5	0.74					
FX32C/Plastiment = 9/1	0.64	0.52	0.61	0.33	0.32	0.38
FX32C/Plastiment = 8/2	0.57	0.44	0.57	0.24	0.26	0.35
FX32C/Plastiment = 7/3		0.30	0.43	0.20	0.21	0.35
Sikament/Plastiment = 9/1	0.54	0.44	0.55	0.28	0.30	0.32
Sikament/Plastiment = 8/2	0.47	0.40	0.46	0.24	0.26	0.30
Sikament/Plastiment = 7/3	0.43	0.31	0.37	0.23	0.21	0.30
WRDA/Plastiment = 9/1	0.41				0.27	0.28
WRDA/Plastiment = 8/2					0.21	0.26
WRDA/Plastiment = 7/3					0.24	0.25

TABLE 86

Time Dependence of Pat Area

Cement 21731

(D) = 5 min. delayed addition of "A" admixture

w/c	% Adm.	Admixture	Delay Time, min. 0	15	30	60	$\%\Delta A_{60}$
0.45	None		8.45	8.20	8.20	8.11	5.0
0.36	0.60	Lomar D	12.63	10.93	10.83	9.48	29.0
0.36	0.50	Lomar D	9.47	8.27	8.46	6.64	36.8
0.36	0.40	Lomar D	4.99	4.39	3.84	3.01	61.5
0.36	0.40(D)	Lomar D	16.25	15.21	13.57	11.45	33.1
0.36	0.30(D)	Lomar D	12.37	9.86	8.99	7.38	47.0
0.36	0.50	Lomar D/Plastiment = 9/1	9.70	7.90	7.44	6.51	40.2
0.36	0.45	Lomar D/Plastiment = 8/2	10.78	9.16	8.12	6.76	44.6
0.36	0.40	Lomar D/Plastiment = 8/2	7.68	7.94	7.36	7.55	19.1
0.36	0.30(D)	Lomar D/Plastiment = 8/2	8.62	7.02	4.13	5.28	48.8
0.36	0.45	Lomar D/Plastiment = 7/3	8.45	6.08	6.32	7.79	9.9
0.36	0.45	Lomar D/Plastiment = 7/3	9.17	9.95	10.00	9.24	-0.9
0.36	0.40	Lomar D/Plastiment = 7/3	8.85	9.84	8.60	6.88	27.8
0.36	0.40	Lomar D/Plastiment = 7/3	9.80	8.06	7.16	5.85	49.2
0.36	0.40(D)	Lomar D/Plastiment = 7/3	10.65	9.74	8.70	6.70	44.5
0.36	0.30(D)	Lomar D/Plastiment = 7/3	9.30	8.63	7.68	5.99	44.0
0.36	0.60	Melment L-10	11.48	11.65	10.12	5.89	57.6
0.36	0.55	Melment L-10	11.04	9.02	5.87	4.06	75.3
0.36	0.35	Melment L-10	7.83	6.30	5.46	4.19	60.1
0.36	0.50(D)	Melment L-10	19.99	17.83	18.13	15.14	26.6
0.36	0.40(D)	Melment L-10	11.63	8.77	8.15	6.54	51.6
0.36	0.30(D)	Melment L-10	11.45	9.06	7.95	6.12	55.1
0.36	0.65	Melment L-10/Plastiment = 9/1	10.83	9.23	7.88	7.18	40.3
0.36	0.60	Melment L-10/Plastiment = 8/2	8.46	7.94	6.88	5.74	44.6
0.36	0.55	Melment L-10/Plastiment = 8/2	6.64	6.56	5.81	4.65	40.9
0.36	0.55	Melment L-10/Plastiment = 8/2	8.24	7.41	6.56	4.93	51.2
0.36	0.69(D)	Melment L-10/Plastiment = 8/2	11.05	9.13	8.16	6.42	49.9
0.36	0.50	Melment L-10/Plastiment = 7/3	6.04	6.26	5.25	4.96	25.2
0.36	0.40	Melment L-10/Plastiment = 7/3	4.04	4.81	3.99	3.42	27.3
0.36	0.40	Melment L-10/Plastiment = 7/3	4.31	4.71	4.20	3.44	34.3
0.36	0.40(D)	Melment L-10/Plastiment = 7/3	5.82	5.51	4.81	3.98	45.4
0.36	0.50	Mighty 150	9.09	8.01	9.91	6.43	36.3
0.36	0.50	Mighty 150	11.47	9.50	7.02	5.62	60.3
0.36	0.40(D)	Mighty 150	16.09	14.31	14.33	12.81	22.9
0.36	0.30(D)	Mighty 150	10.37	9.65	8.34	7.22	36.6
0.36	0.40	Mighty RD-2	9.06	8.80	7.69	7.16	34.3
0.36	0.40	Mighty RD-2	12.73	11.80	11.81	8.49	38.7
0.36	0.45	Mighty 150/Plastiment = 9/1	8.53	7.20	6.44	5.24	48.7
0.36	0.45	Mighty 150/Plastiment = 8/2	8.93	8.55	7.32	6.51	33.8
0.36	0.40	Mighty 150/Plastiment = 7/3	8.11	9.22	8.38	7.34	12.1
0.36	0.30(D)	Mighty 150/Plastiment = 7/3	9.01	8.30	7.70	6.38	36.3
0.36	0.45	Lomar D/Daratard HC = 7/3	5.45	4.15	3.73	3.25	59.8
0.36	0.50	Lomar D/Pozzolith 100XR = 9/1	7.11	6.17	5.27	4.29	52.8
0.36	0.50	Lomar D/Pozzolith 100XR = 7/3	6.58	4.24	3.03	3.31	68.0

TABLE 86 (Continued)

Time Dependence of Pat Area

Cement 21731

(D) = 5 min. delayed addition of "A" admixture

w/c	% Adm.	Admixture	Delay Time, min. 0	15	30	60	$\%\Delta A_{60}$
0.36	0.55	FX-32C	6.47	4.55	3.58	2.92	75.5
0.36	0.40(D)	FX-32C	15.39	14.15	11.59	10.90	33.0
0.36	0.35(D)	FX-32C	11.10	9.12	8.46	6.30	51.4
0.36	0.45	Sikament	9.14	7.41	6.39	5.11	54.7
0.36	0.40(D)	Sikament	22.41	21.13	19.15	17.21	25.2
0.36	0.30(D)	Sikament	11.47	9.83	8.41	7.65	39.4
0.36	0.45	WRDA-19	8.87	7.07	6.20	4.14	66.6
0.36	0.40(D)	WRDA-19	20.36	19.46	18.44	17.81	13.7
0.36	0.30(D)	WRDA-19	13.76	11.31	10.42	9.24	37.7
0.36	1.25	Alkanol	7.30	7.02	6.54	6.24	19.2
0.36	1.50	Alkanol	8.32	7.45	7.50	6.99	20.3
0.36	1.75	Alkanol	8.56	8.10	8.35	7.76	11.8
0.36	1.25(D)	Alkanol	8.77	9.44	8.85	8.36	5.9

TABLE 87

Time Dependence of Pat Area

Cement 21732

w/c	% Adm.	Admixture	Delay Time, min. 0	15	30	60	$\%\Delta A_{60}$
0.45	None		6.83	7.00	6.87	6.87	0
0.36	0.45	Lomar D	8.88	7.38	6.63	4.97	55.0
0.36	0.40	Lomar D	5.90	4.95	4.41	3.74	52.3
0.36	0.35	Lomar D/Plastiment = 9/1	7.29	5.81	4.87	3.80	61.6
0.36	0.40	Lomar D/Plastiment = 8/2	7.67	8.58	8.12	7.47	3.4
0.36	0.40	Lomar D/Plastiment = 8/2	8.71	8.62	7.93	6.98	24.9
0.36	0.40	Lomar D/Plastiment = 7/3	9.63	7.46	6.64	6.33	42.0
0.36	0.55	Melment L-10	7.46	5.71	4.80	3.84	63.6
0.36	0.55	Melment L-10/Plastiment = 9/1	10.22	6.06	6.09	5.01	61.7
0.36	0.50	Melment L-10/Plastiment = 8/2	19.77	7.54	5.31	4.81	83.1
0.36	0.50	Melment L-10/Plastiment = 8/2	7.65	7.54	6.69	5.43	37.8
0.36	0.45	Melment L-10/Plastiment = 7/3	10.14	7.53	6.34	6.31	45.8
0.36	0.40	Melment L-10/Plastiment = 7/3	5.74	5.81	5.40	5.37	10.1
0.36	0.40	Melment L-10/Plastiment = 7/3	9.10	5.88	4.46	3.58	75.3
0.36	0.40	Mighty 150	7.99	6.86	5.73	4.93	49.2
0.36	0.40	Mighty 150/Plastiment = 9/1	9.47	9.24	7.95	6.97	32.5
0.36	0.35	Mighty 150/Plastiment = 9/1	6.39	5.98	5.58	4.58	39.2
0.36	0.45	Lomar D/Pozzolith 100XR = 9/1	9.74	8.11	5.04	3.98	72.3

TABLE 88

Time Dependence of Pat Area

Cement 21733

(D) = 5 min. delayed addition of "A" admixture

w/c	% Adm.	Admixture	Delay Time, min. 0	15	30	60	$\%\Delta A_{60}$
0.45	None		6.91	6.81	6.62	6.39	10.1
0.36	0.40	Lomar D	6.41	5.72	4.85	3.92	53.7
0.36	0.35	Lomar D	4.64	3.87	3.53	2.98	57.8
0.36	0.45	Lomar D/Plastiment = 9/1	7.59	6.64	6.02	5.43	37.1
0.36	0.40	Lomar D/Plastiment = 8/2	5.85	5.59	5.19	4.58	31.1
0.36	0.45	Lomar D/Plastiment = 7/3	9.22	8.70	8.69	7.46	23.6
0.36	0.50	Melment L-10	7.34	6.66	5.44	4.24	55.7
0.36	0.55(D)	Melment L-10	13.33	12.68	12.33	10.93	20.8
0.36	0.50	Melment L-10/Plastiment = 9/1	5.87	5.43	5.10	4.05	44.3
0.36	0.50	Melment L-10/Plastiment = 9/1	6.04	5.38	4.61	4.27	41.5
0.36	0.50	Melment L-10/Plastiment = 9/1	5.73	4.74	4.76	3.73	50.5
0.36	0.50	Melment L-10/Plastiment = 9/1	4.59	4.12	3.80	3.43	41.1
0.36	0.50	Melment L-10/Plastiment = 8/2	5.41	6.87	6.87	5.63	-6.0
0.36	0.50	Melment L-10/Plastiment = 8/2	6.37	6.94	6.76	5.36	22.0
0.36	0.55	Melment L-10/Plastiment = 7/3	7.54	5.49	5.68	5.26	39.5
0.36	0.50	Melment L-10/Plastiment = 7/3	6.83	5.97	6.16	5.51	26.1
0.36	0.40	Mighty 150	6.99	6.40	5.77	4.90	40.0
0.36	0.40	Mighty 150/Plastiment = 9/1	5.41	4.45	4.49	3.84	43.1
0.36	0.45	Mighty 150/Plastiment = 8/2	6.65	8.29	8.11	7.53	-18.0
0.36	0.45(D)	Mighty 150/Plastiment = 8/2	7.86	7.54	6.73	5.74	34.8
0.36	0.40	Lomar D/Pozzolith 100XR = 9/1	4.25	3.80	3.52	2.99	50.8

TABLE 89

Time Dependence of Pat Area

Cement MCC-274

w/c	% Adm.	Admixture	Delay Time, min. 0	15	30	60	$\%\Delta A_{60}$
0.45	None		8.20	8.10	7.97	7.61	9.2
0.36	0.275	Lomar D	10.35	6.15	5.42	4.32	70.3
0.36	0.25	Lomar D/Plastiment = 9/1	7.48	6.35	5.30	4.16	58.1
0.36	0.25	Lomar D/Plastiment = 8/2	14.88	7.32	6.03	4.82	76.7
0.36	0.20	Lomar D/Plastiment = 8/2	8.23	6.16	5.55	4.35	60.1
0.36	0.20	Lomar D/Plastiment = 7/3	10.03	6.45	5.61	4.32	69.1
0.36	0.35	Melment L-10	8.01	6.53	5.87	5.10	46.6
0.36	0.30	Melment L-10/Plastiment = 9/1	7.21	8.87	6.67	5.36	34.0
0.36	0.25	Melment L-10/Plastiment = 9/1	10.68	7.02	6.13	5.08	62.9
0.36	0.25	Melment L-10/Plastiment = 8/2	9.04	7.49	6.45	5.29	51.6
0.36	0.20	Melment L-10/Plastiment = 8/2	6.23	6.04	4.99	4.30	43.3
0.36	0.20	Melment L-10/Plastiment = 7/3	8.76	7.60	5.36	5.44	47.5
0.36	0.20	Melment L-10/Plastiment = 7/3	8.71	6.33	5.28	4.21	64.8
0.36	0.25	Mighty 150	8.08	5.70	5.07	4.14	62.4
0.36	0.22	Mighty 150	7.40	6.79	4.50	3.24	73.9
0.36	0.25	Mighty 150/Plastiment = 9/1	9.60	8.03	6.40	4.64	63.3
0.36	0.20	Mighty 150/Plastiment = 8/2	9.53	7.16	6.27	4.80	61.0
0.36	0.25	Lomar D/Pozzolith 100XR = 9/1	6.87	5.71	4.53	3.68	62.5

TABLE 90

Time Dependence of Pat Area

LTS-25

(D) = 5 min. delayed addition of "A" admixture

w/c	% Adm.	Admixture	Delay Time, min. 0	15	30	60	$\%\Delta A_{60}$
0.45	None		11.92	12.21	11.42	10.87	10.3
0.36	0.35	Lomar D	9.91	9.90	9.25	7.46	30.1
0.36	0.30	Lomar D	7.81	7.76	7.27	6.23	26.2
0.36	0.35(D)	Lomar D	26.48	26.94	28.18	27.71	-5.0
0.36	0.25(D)	Lomar D	19.02	18.91	16.92	12.95	35.2
0.36	0.20(D)	Lomar D	14.89	13.53	12.35	10.59	32.8
0.36	0.15(D)	Lomar D	11.52	10.35	9.26	5.39	62.9
0.36	0.35	Lomar D/Plastiment = 9/1	12.96	11.78	11.55	10.44	22.5
0.36	0.35	Lomar D/Plastiment = 8/2	15.50	12.45	12.62	12.10	24.8
0.36	0.30	Lomar D/Plastiment = 8/2	8.48	8.73	8.91	7.23	18.6
0.36	0.30	Lomar D/Plastiment = 7/3	18.49	8.86	8.69	7.29	67.0
0.36	0.30	Lomar D/Plastiment = 7/3	18.94	9.36	9.56	9.36	55.9
0.36	0.20(D)	Lomar D/Plastiment = 7/3	11.25	8.61	8.22	7.84	36.0
0.36	0.50	Melment L-10	12.59	14.65	12.63	10.37	20.5
0.36	0.45	Melment L-10	8.26	7.80	7.01	6.18	32.0
0.36	0.30(D)	Melment L-10	21.33	18.59	18.89	16.14	26.5
0.36	0.20(D)	Melment L-10	11.44	10.05	9.39	8.43	31.1
0.36	0.45	Melment L-10/Plastiment = 9/1	12.47	12.92	12.08	12.15	3.0
0.36	0.45	Melment L-10/Plastiment = 9/1	15.65	15.75	16.04	13.48	15.6
0.36	0.40	Melment L-10/Plastiment = 8/2	15.24	11.83	12.49	10.84	32.7
0.36	0.35	Melment L-10/Plastiment = 8/2	10.15	10.17	9.13	8.01	25.5
0.36	0.30	Melment L-10/Plastiment = 7/3	9.87	8.46	9.19	7.63	27.7
0.36	0.30(D)	Melment L-10/Plastiment = 7/3	19.19	7.84	7.37	6.95	70.3
0.36	0.25(D)	Melment L-10/Plastiment = 7/3	11.94	7.34	6.79	6.40	54.5
0.36	0.35	Mighty 150	11.34	12.25	11.60	10.06	13.4
0.36	0.30	Mighty 150	9.20	8.98	8.24	7.00	29.6
0.36	0.25(D)	Mighty 150	19.70	19.58	18.85	17.45	12.5
0.36	0.20(D)	Mighty 150	16.00	15.11	14.42	11.92	28.7
0.36	0.15(D)	Mighty 150	11.00	10.03	9.70	8.20	30.3
0.36	0.30	Mighty 150/Plastiment = 9/1	9.50	9.72	9.11	8.17	17.2
0.36	0.15(D)	Mighty 150/Plastiment = 9/1	9.74	7.88	6.98	5.93	47.8
0.36	0.30	Mighty 150/Plastiment = 8/2	12.83	10.94	10.43	9.39	31.1
0.36	0.25	Mighty 150/Plastiment = 7/3	10.56	8.02	7.29	6.78	43.0
0.36	0.25	Lomar D/Daratard HC = 7/3	6.84	6.63	6.18	5.48	26.8
0.36	0.35	Lomar D/Pozzolith 100XR = 9/1	8.13	7.79	6.62	5.99	33.6
0.36	0.25	Lomar D/Pozzolith 100XR = 7/3	6.63	6.14	5.97	5.12	31.1
0.36	0.35	FX-32C	7.60	6.76	6.47	5.99	27.6
0.36	0.25(D)	FX-32C	21.65	19.33	23.07	17.97	18.5
0.36	0.20(D)	FX-32C	13.10	11.60	9.67	9.25	34.0
0.36	0.30	Sikament	8.69	7.52	6.26	5.61	44.5
0.36	0.25(D)	Sikament	19.94	22.02	21.08	19.16	4.3
0.36	0.20(D)	Sikament	16.49	15.08	14.34	12.58	26.6

TABLE 90 (Continued)

Time Dependence of Pat Area

LTS-25

(D) = 5 min. delayed addition of "A" admixture

w/c	% Adm.	Admixture	Delay Time, min. 0	15	30	60	$\%\Delta A_{60}$
0.36	0.30	WRDA-19	9.41	8.47	7.62	6.70	35.5
0.36	0.25(D)	WRDA-19	19.90	19.63	19.27	17.18	15.0
0.36	0.20(D)	WRDA-19	16.27	14.99	13.53	11.87	30.3
0.36	0.60	Alkanol	10.79	11.19	11.02	10.67	1.3
0.36	0.60(D)	Alkanol	16.28	15.72	16.18	16.88	-4.1

TABLE 91

Time Dependence of Pat Area

Cement MCC-287

(D) = 5 min. delayed addition of "A" admixture

w/c	% Adm.	Admixture	Delay Time, min. 0	15	30	60	$\%\Delta A_{60}$
0.45	None		11.63	9.94	10.76	10.34	13.1
0.36	0.30	Lomar D	13.84	12.52	11.64	9.89	32.7
0.36	0.20(D)	Lomar D	15.77	12.00	10.74	8.53	51.7
0.36	0.30	Lomar D/Plastiment = 9/1	17.66	16.68	13.01	10.36	45.9
0.36	0.30	Lomar D/Plastiment = 7/3	13.08	14.14	12.54	11.35	15.3
0.36	0.20(D)	Lomar D/Plastiment = 7/3	13.18	10.24	8.61	7.31	51.4
0.36	0.15(D)	Lomar D/Plastiment = 7/3	7.34	5.24	4.63	3.60	67.1
0.36	0.35	Melment L-10	11.20	9.24	8.58	7.17	42.7
0.36	0.35	Melment L-10	13.17	10.47	9.50	8.14	44.1
0.36	0.30	Melment L-10	13.56	8.66	7.90	6.97	55.9
0.36	0.20(D)	Melment L-10	12.41	10.04	8.31	7.36	47.5
0.36	0.20	Melment L-10/Plastiment = 7/3	7.53	5.67	5.09	4.26	46.8
0.36	0.25(D)	Melment L-10/Plastiment = 7/3	12.10	9.53	7.86	6.63	53.0
0.36	0.20(D)	Melment L-10/Plastiment = 7/3	12.80	7.23	6.75	5.71	64.3
0.36	0.25	Mighty 150	12.12	10.77	9.74	8.76	32.5
0.36	0.20(D)	Mighty 150	24.97	15.77	13.85	12.14	55.3
0.36	0.15(D)	Mighty 150	11.25	8.99	7.74	6.65	48.5
0.36	0.25	Mighty 150/Plastiment = 7/3	11.26	10.31	9.30	8.32	31.0
0.36	0.15(D)	Mighty 150/Plastiment = 7/3	8.58	6.87	6.12	5.48	45.5
0.36	0.35	Lomar D/Pozzolith 100XR = 9/1	11.76	10.94	8.34	7.40	43.6
0.36	0.35	FX-32C	12.97	10.81	9.29	7.74	46.7
0.36	0.30	Sikament	16.17	13.73	12.20	10.00	42.8
0.36	0.30	WRDA-19	15.45	13.11	11.78	10.36	37.2

APPENDIX D

TABLE 92

Chemical Composition of Cements

Cement (Lot No.)	Oxide Analysis										Blaine Fineness (cm^2/gm)	Potential Compound Composition				C_3A (XRD)
	SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	MgO	K_2O	Na_2O	Alkalies (as Na_2O)	Free Lime		C_3S	C_2S	C_3A	C_4AF	
MCC-274	22.42	4.57	3.11	65.82	0.34	2.93	0.40	0.08	0.35	0.63	3440	59.9	19.1	6.9	9.5	1.9
MCC-275A	21.47	6.19	2.54	67.26	0.08	1.26	0.14	0.14	0.23	1.02	3439	61.3	15.3	12.1	7.7	7.1
MCC-276	20.96	5.02	2.34	63.30	2.90	3.51	0.17	0.16	0.27	0.50	3630	51.0	21.6	9.3	7.1	4.6
21731	20.48	5.00	2.46	63.39	2.76	2.71	0.99	0.13	0.78	1.48	3738	57.4	19.9	9.1	7.5	4.9
21732	20.92	4.86	3.09	63.85	2.63	2.01	0.66	0.17	0.60	0.98	3513	56.4	17.5	7.7	9.4	2.4
21733	21.73	4.46	2.59	62.95	2.96	3.06	1.00	0.07	0.73	0.69	3186	46.2	27.4	7.4	7.9	4.1
21763	20.91	4.89	3.24	63.45	2.66	1.99	0.73	0.16	0.64	-	3833	54.3	19.0	7.5	9.9	2.0
21782	21.77	5.52	2.73	65.30	2.50	0.81	0.62	0.17	0.58	1.10	3241	47.8	26.4	10.0	8.3	4.2
21783	22.14	4.36	4.80	63.85	2.37	0.69	0.41	0.08	0.35	1.02	3196	44.7	29.8	3.4	14.6	2.8
21784	20.20	5.54	2.32	63.28	3.45	3.24	-	-	0.90	0.74	3845	50.7	19.7	7.1	10.8	5.5
21785	21.28	5.04	4.54	61.79	2.39	3.24	-	-	0.90	0.40	3362	41.0	30.1	5.7	13.8	2.0
21795	21.17	5.04	2.92	62.64	2.68	2.40	0.58	0.32	0.70	1.69	3748	41.6	29.3	8.4	8.9	4.1
21796	21.71	3.73	4.65	63.63	2.98	0.73	0.51	0.13	0.47	-	2937	53.8	21.6	2.0	14.1	2.8
21802	20.95	5.52	3.13	62.26	2.68	2.97	0.51	0.24	0.58	1.97	4179	41.0	29.2	9.3	9.5	5.0
21813	21.82	4.09	3.30	61.44	2.63	4.14	0.66	0.23	0.66	1.92	3770	44.6	28.9	5.3	10.0	2.0
21817	20.83	4.80	3.16	63.09	2.85	1.94	0.78	0.19	0.70	-	4054	53.6	19.3	7.4	9.6	1.9
21818	21.12	4.83	2.54	61.98	2.48	3.51	0.70	0.09	0.55	-	3584	48.7	23.8	8.5	7.7	3.3

APPENDIX E

Materials, Mix Designs, and Properties of Fresh Concretes for Mixtures Used in Preparation of Concrete Specimens

1. Tests 1-11

Mixtures were designed for cement content of 658 lb/yd^3 (390 kg/m^3) and maximum aggregate size of 0.75 inch (19 mm). A slump of 2-3 inches (51-76 mm) and air content of 6$\pm$ 1% were used for control mixtures. Slumps of 5-6 inches (127-152 mm) and air contents of 7-8% were used for the mixtures containing SWR.

Aggregates used were Thornton limestone and Elgin sand. Relevant aggregate data are given in Table 10 (pg. 31). These were the same aggregates used in the earlier laboratory evaluations. A commercial Type I cement (lot No. 21817) having relatively high alkali content and fineness was used for all mixtures. Neutralized Vinsol resin in 2% solution was used in all mixtures. The SWR Mighty-150 and Melment L-10 were used where indicated.

Coarse aggregate was weighed air-dry, then soaked overnight prior to batching. Fine aggregate was used in the damp condition, moisture content ranging from 2-3 percent. All mixing was done in an open-pan counter-current mixer rated at 6.5 ft^3 (0.18 m^3) (Cumflow^R Model 1A, Liner Concrete Machinery, Ltd., Gateshead, Gt. Britian). Control mixtures were mixed for 3 minutes, then discharged. SWR mixtures were mixed without SWR for 3 minutes, the pan was then covered with a plastic sheet for 17 minutes. The SWR was then added and the batch mixed an additional 90 sec., then discharged.

Mix proportions and admixture dosages are given in Table 93.

For control and Mighty-150 mixtures all test specimens except those for test Nos. 1 (shrinkage upon set), 3 (flexural strength), and 8 (fatigue) were cast from 4.5 ft^3 batches (0.13 m^3) cast on three separate days. Test specimens for test Nos. 3 and 8 were large 6x6x30-in. (152x152x762 mm) beams cast from separate 6.0-ft^3 (0.17 m^3) batches cast on two separate days. Test specimens for test No. 1 were cast from separate 1.0 cf (0.03 m^3) batches.

For Melment L-10 mixtures all specimens were cast from 6.1-ft^3 (0.17 m^3) batches.

Slump, air content, and unit weight records for all batches are shown in Table 94. Also included are the tests for which specimens were cast from each batch.

2. Tests 12 and 13

Mix designs and aggregates for these tests were identical to those used for Tests 1-11. In addition to the Type I cement (21817), a second Type I cement (21818) having low alkali content and fineness was used, as this cement was found to have a lower SWR dosage requirement based on the "mini-slump" results. All batches were mixed in an open-pan counter-current type mixer (Lancaster Model SW, Posey Iron Works, Lancaster, PA) having a capacity of 1.5 ft^3 (0.04 m^3). Mix cycles for control and SWR batches were the same as for the batches described in the previous section. Mix proportions and admixture dosages are given in Table 95, properties of fresh concrete mixtures in Table 96.

3. Test 14 (Resistance to Sulfate Attack)

As sulfate resistance of concrete is highly dependent on cement composition, a number of cements were added to this part of the program. These included the previous commercial Type I (No. 21817), a high C_3A cement (LTS 18), and a low C_3A Type V cement (LTS 51). In addition a Class F fly ash known to be beneficial in terms of sulfate resistance (27) was used as a replacement for 20 percent of both the high C_3A and commercial cements. Chemical analyses are given in Table 97A-B. Mix designs, aggregates, and mix cycles were the same as utilized in previous mixtures (see Tests 12 and 13). Mix proportions and admixture dosages are given in Table 98. Only Mighty-150 was used as SWR.

Proportions of the fresh concrete mixtures are given in Table 99.

4. Test 15 (Resistance to D-Cracking)

An aggregate which has shown problems with poor durability attributable to D-cracking was obtained from a quarry in Menlo, Iowa. Properties of the aggregate (Argentine limestone) are shown in Table 100.

Aggregate was used as-received (not regraded). The cement used was No. 21817 (see Appendix D). Mixtures were prepared with and without Mighty-150. Mix designs and mix cycles were the same as used in the previous batches. Mix proportions and properties of fresh concretes are shown in Table 101 and 102.

5. Test 16
(Chloride Permeability and Potential for Reinforcing Steel Corrosion)

For these mixtures an aggregate having low chloride content was needed. The aggregates selected were siliceous sand and gravel from Eau Claire, Wisconsin. These aggregates have historically exhibited chloride levels (as Cl^-) less than 0.01% by weight of sample. Aggregate properties are given in Table 103.

Cement No. 21817 was used in all mixtures. Mighty-150 and Melment L-10 were used as SWR.

Concrete mixtures were designed for 2-3 inches (51-76 mm) of slump and 6±1% air content for the controls, and 5-6 inches (127-152 mm) of slump and 7-8% air content for the batches containing SWR. The particular aggregates used have a very low water demand, which dictated the use of lower cement contents than in the previous batches. If cement contents equal to those of the previous mixtures had been used, control water-cement ratios would have been very low at the design slump levels, leading to abnormally long time-to-corrosion. Use of a lower cement content allowed adjustment of control water-cement ratio to the range of 0.40-0.45, more typical of actual field concrete. Therefore, cement contents of approximately 520 lb/yd^3 (309 kg/m^3) were used in all mixtures. Mix proportions and admixture dosages are given in Table 104.

Properties of fresh concrete mixtures are given in Table 105.

TABLE 93

Concrete Mix Proportions

Tests 1-11

Mixture	SWR Dosage (% s/c)	NVR (ml/lb)1/	w/c Ratio	Quantities lb per cu yd2/ - SSD: Water	Cement	Sand	Coarse Aggregate	% Sand Abs. Vol.
1. Control	None	2.2	0.40	270	671	1,175	1,758	40
2. Mighty-150	0.50	6.9	0.34	222	660	1,288	1,713	43
3. Melment L-10	0.69	12.0	0.34	225	658	1,283	1,700	43

TABLE 94

Characteristics of Fresh Concrete Used for Test Nos. 1-11

No.	Description	Slump (in.)4/	Air Content (%)	Unit Weight (lb/ft^3)5/	Specimen Cast for Test Nos.
1.1 A	Control - 4.5 ft^3 3/	2.0	5.6	144.2	2, 4, 5, 6, 7, 9, 10, 11
1.1 B	Control - 4.5 ft^3	2.5	6.8	143.6	2, 4, 5, 6, 7, 9, 10, 11
1.1 C	Control - 4.5 ft^3	2.3	5.1	145.6	2, 4, 5, 6, 7, 9, 10, 11
1.2 A	Control - 6.0 ft^3	2.3	6.6	143.2	3, 8
1.2 B	Control - 6.0 ft^3	2.0	5.5	145.2	3, 8
1.3	Control - 1.0 ft^3	2.4	5.6	-	1
2.1 A	Mighty-150 - 4.5 ft^3	6.0	7.4	146.2	2, 4, 5, 6, 7, 9, 10, 11
2.1 B	Mighty-150 - 4.5 ft^3	5.9	7.4	142.8	2, 4, 5, 6, 7, 9, 10, 11
2.1 C	Mighty-150 - 4.5 ft^3	6.0	7.6	144.2	2, 4, 5, 6, 7, 9, 10, 11
2.2 A	Mighty-150 - 6.0 ft^3	5.0	7.8	145.0	3, 8
2.2 B	Mighty-150 - 6.0 ft^3	5.5	7.2	145.6	3, 8
2.3	Mighty-150 - 1.0 ft^3	5.2	7.8	-	1
3.1 A	Melment L-10 - 6.1 ft^3	5.2	7.6	144.6	2, 3, 4, 6
3.1 B	Melment L-10 - 6.1 ft^3	5.7	8.0	143.2	2, 3, 4, 6
3.1 C	Melment L-10 - 6.1 ft^3	5.8	7.6	144.8	2, 3, 4, 6

TABLE 95

Mixture Proportions and Admixture Dosages

Tests 12-13

Mix	Cement	SWR Dosage (% s/c)	NVR (ml/lb)1/	w/c Ratio	Quantities, lb per cu yd2/ - SSD: Water	Cement	Sand	Coarse Aggre-gate	% Sand Abs. Vol.
4.1 Control	21817	-	2.4	0.42	275	656	1,168	1,751	40
4.2 Mighty-150	21817	0.41	8.5	0.35	228	651	1,271	1,699	43
4.3 Melment L-10	21817	0.50	13.4	0.35	228	652	1,274	1,702	43
5.1 Control	21818	-	2.5	0.41	266	655	1,176	1,764	40
5.2 Mighty-150	21818	0.34	5.7	0.35	229	655	1,282	1,714	43
5.3 Melment L-10	21818	0.42	6.7	0.35	230	657	1,287	1,708	43

1/ To convert from ml/lb to ml/kg multiply by 2.20
2/ To convert from lb/yd^3 to kg/m^3 multiply by 0.594
3/ To convert from ft^3 to m^3 multiply by 0.0283
4/ To convert from inches to mm multiply by 25.4
5/ To convert from lb/ft^3 to kg/m^3 multiply by 16.038

TABLE 96

Properties of Fresh Concrete Mixtures

Tests 12-13

No.	SWR	Cement	Slump 1/ (in.)	Air Content (%)	Unit Weight 2/ (lb/ft^3)
4.1	None	21817	2.8	6.2	143.7
4.2	Mighty-150	21817	5.7	8.0	146.1
4.3	Melment L-10	21817	6.0	7.8	144.1
5.1	None	21818	2.7	6.5	144.1
5.2	Mighty-150	21818	5.6	7.4	-
5.3	Melment L-10	21818	5.7	7.1	144.7

1/ To convert from inches to mm multiply by 25.4
2/ To convert from lb/ft^3 to kg/m^3 multiply by 16.038

TABLE 97A

Chemical Analyses of Cements

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	MgO	K_2O	Na_2O	Alkalies (as Na_2O)	Blaine Fineness (cm^2/g)	Potential Compound Composition C_3S	C_2S	C_3A	C_4AF
LTS-18	21.5	6.4	2.3	64.0	1.8	2.6	0.13	0.12	0.21	3268	44.5	28.0	13.2	6.8
LTS-51	24.5	3.5	3.3	64.3	1.4	1.7	0.22	0.08	0.22	3483	41.0	39.0	3.7	10.0

TABLE 97B

Chemical Analysis 1/ of Fly Ash

	SiO_2	Al_2O_3	Fe_2O_3	S + A + F	Free CaO	Total CaO	MgO	SO_3	Alkalis, (as Na_2O)	L.O.I.
M-6498	46.1	19.0	18.6	83.7	2.2	8.2	1.3	1.6	0.72	2.0

1/ Chemical analysis of fly ash No. M-6498 taken from Ref. 27, page 5.

TABLE 98

Mixture Proportion and Admixture Dosages

Test 14

No.	Cement	SWR Dosage (% s/c)	NVR (ml/lb) 1/	w/c Ratio	Quantities, lb per cu yd 2/ - SSD: Water	Cement	Sand	Coarse Aggregate	Fly Ash	% Sand Abs. Vol.
6.1	21817	None	2.2	0.42	284	670	1,159	1,754	-	40
6.2	21817	0.49	7.6	0.36	239	656	1,252	1,691	-	43
6.3	21817 + 20% M-6498	None	2.3	0.40	261	525	1,126	1,801	132	38
7.1	LTS-18	None	2.4	0.42	277	659	1,175	1,763	-	40
7.2	LTS-18	0.54	7.5	0.35	231	659	1,281	1,711	-	43
7.3	LTS-18 + 20% M-6498	None	2.5	0.40	264	526	1,125	1,799	132	38
8.1	LTS-51	None	2.1	0.41	271	660	1,188	1,782	-	40

1/ To convert from ml/lb to ml/kg multiply by 2.20
2/ To convert from lb/yd^3 to kg/m^3 multiply by 0.594

TABLE 99

Properties of Fresh Concrete Mixtures

Test 14

No.	SWR	Cement	Slump (in.) 3/	Air Content (%)	Unit Weight (lb/ft^3) 4/
6.1	None	21817	2.4	5.6	-
6.2	Mighty-150	21817	5.2	7.8	-
6.3	None	21817 + 20% M-6498	2.7	6.2	143.2
7.1	None	LTS-18	2.3	5.8	145.5
7.2	Mighty-150	LTS-18	6.0	7.4	145.1
7.3	None	LTS-18 + 20% M-6498	2.7	6.2	142.0
8.1	None	LTS-51	3.2	5.7	145.9

TABLE 100

Properties of Argentine Limestone Aggregate

Maximum Size	Grading - % Retained on Sieve Size Indicated: 0.75-in.	0.375-in.	No. 4 5/	No. 8 6/	Bulk Sp.Gr. (SSD)	24-hour Absorption (% - SSD)
0.75-inch 3/	3.9	58.9	93.2	98.9	2.68	1.2

3/ To convert from inches to mm multiply by 25.4
4/ To convert from lb/ft^3 to kg/m^3 multiply by 16.038
5/ No. 4 U.S. sieve = 4.75 mm
6/ No. 8 U.S. sieve = 2.36 mm.

TABLE 101

Mixture Proportions of Concrete

Test 15

No.	Mighty-150 Dosage (% s/c)	NVR (ml/lb) 1/	w/c Ratio	Quantities-lb per cu yd 2/-SSD: Water	Cement	Sand	Coarse Aggregate	% Sand Abs. Vol.
9.1	None	2.3	0.43	284	656	1,316	1,641	44
9.2	0.54	11.5	0.35	226	653	1,436	1,578	48

TABLE 102

Properties of Fresh Concrete

Test 15

No.	SWR	Slump (in.) 3/	Air Content (%)
9.1	None	2.0	5.0
9.2	Mighty-150	5.3	7.2

1/ To convert from ml/lb to ml/kg multiply by 2.20
2/ To convert from lb/yd^3 to kg/m^3 multiply by 0.594
3/ To convert from inches to mm multiply by 25.4

TABLE 103

Properties of Aggregates

Test 16

- Eau Claire Gravel -

Maximum Size	Grading - % Retained on Sieve Size Indicated: 0.75-in.	0.375-in.	No. 4 2/	Bulk Sp.Gr. (SSD)	24-hour Absorption (% - SSD)
0.75-inch 1/	0	50	100	2.26	1.5

- Eau Claire Sand -

Bulk Sp. Gr. (SSD)	24-hour Absorption (% - SSD)	F.M.
2.59	1.5	3.00

TABLE 104

Mixture Proportions and Admixture Dosages

Test 16

No.	SWR	Dosage (% s/c)	NVR (ml/lb) 3/	w/c Ratio	Quantities (lb per cu yd 4/ - SSD): Water	Cement	Sand	Gravel	% Sand Abs. Vol.
10.1	None	-	2.6	0.43	218	511	1,350	1,760	44
10.2	Mighty-150	0.54	5.4	0.35	181	517	1,382	1,803	44
10.3	Melment L-10	0.63	8.5	0.35	181	516	1,379	1,800	44

TABLE 105

Properties of Fresh Concrete Mixtures

Test 16

No.	SWR	Slump (in.) 1/	Air Content (%)	Unit Weight (lb/ft^3) 5/
10.1	None	2.4	7.0	141.8
10.2	Mighty-150	5.3	7.4	142.4
10.3	Melment L-10	6.0	7.5	141.4

1/ To convert from inches to mm multiply by 25.4
2/ No. 4 U.S. sieve = 4.75 mm
3/ To convert from ml/lb to ml/kg multiply by 2.20
4/ To convert from lb/yd^3 to kg/m^3 multiply by 0.594
5/ To convert from lb/ft^3 to kg/m^3 multiply by 16.038

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FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH AND DEVELOPMENT

The Offices of Research and Development (R&D) of the Federal Highway Administration (FHWA) are responsible for a broad program of staff and contract research and development and a Federal-aid program, conducted by or through the State highway transportation agencies, that includes the Highway Planning and Research (HP&R) program and the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board. The FCP is a carefully selected group of projects that uses research and development resources to obtain timely solutions to urgent national highway engineering problems.*

The diagonal double stripe on the cover of this report represents a highway and is color-coded to identify the FCP category that the report falls under. A red stripe is used for category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, green for categories 6 and 7, and an orange stripe identifies category 0.

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion, and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements that affect the quality of the human environment. The goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge and technology of materials properties, using available natural materials, improving structural foundation materials, recycling highway materials, converting industrial wastes into useful highway products, developing extender or substitute materials for those in short supply, and developing more rapid and reliable testing procedures. The goals are lower highway construction costs and extended maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highways at reasonable costs.

6. Improved Technology for Highway Construction

This category is concerned with the research, development, and implementation of highway construction technology to increase productivity, reduce energy consumption, conserve dwindling resources, and reduce costs while improving the quality and methods of construction.

7. Improved Technology for Highway Maintenance

This category addresses problems in preserving the Nation's highways and includes activities in physical maintenance, traffic services, management, and equipment. The goal is to maximize operational efficiency and safety to the traveling public while conserving resources.

0. Other New Studies

This category, not included in the seven-volume official statement of the FCP, is concerned with HP&R and NCHRP studies not specifically related to FCP projects. These studies involve R&D support of other FHWA program office research.

* The complete seven-volume official statement of the FCP is available from the National Technical Information Service, Springfield, Va. 22161. Single copies of the introductory volume are available without charge from Program Analysis (HRD-3), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.